1951

Mechanism of moisture movement in the drying of organic granular solids

Edward W. Jerger
Iowa State College

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps.

ProQuest Information and Learning
300 North Zeeb Road, Ann Arbor, MI 48106-1346 USA
800-521-0600

MECHANISM OF MOISTURE MOVEMENT IN THE DRYING OF ORGANIC GRANULAR SOLIDS

by

Edward W. Jerger

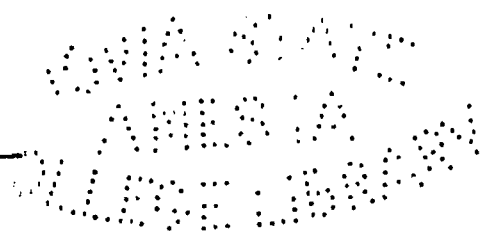
A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Theoretical and Applied Mechanics

Approved:

Signature was redacted for privacy.

In Charge of Major Work



Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State College

1951

UMI Number: DP13303

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

TABLE OF CONTENTS

Page

ABBREVIATIONS

atm	atmospheres
cm	centimeters
cfm	cubic feet per minute
DS	dry solid
fpm	feet per minute
gm	grams
hp	horsepower
hr	hours
in.	inches
lb	pound
psi	pounds per square inch
psf	pounds per square foot
sq ft	square feet
sq cm	square centimeters
rpm	revolutions per minute
^{o}F	temperature in degrees Fahrenheit
^{o}C	temperature in degrees centigrade

INTRODUCTION

Definition of Drying

In general, the term drying is loosely used to describe a process of liquid or vapor removal from solids, liquids, or gases. Consequently, the term drying is often so misapplied that the true significance of drying is confused. A rigorous definition of drying would exclude many of the "so-called " industrial drying applications.

Drying, then, is uniquely defined as the partial or complete removal of evaporable liquids from a mixture of the liquid with the solids, other liquids, or gases; by thermal means. The inclusion of the restriction, "by thermal means," separates true drying from a mechanical separation of liquids from a mixture of the liquid with solids, other liquids, or gases. Yet it is still difficult to distinguish between drying and evaporation or distillation. In fact, there is only a hair line difference between them, and it appears that the difference is based merely on the nature of the equipment used in each process.

A striking example of the misuse of the term drying is illustrated in the industrial reference to the drying of paints and varnishes. Paints and varnishes (in accordance with the

definition of drying) are not dried at all, but are hardened or fixed by the evaporation of their volatile solvents and by the oxidation of their "so-called" drying oil, usually linseed.

Mechanical methods of liquid separation previously referred to may be classified as: settling, decantation, filtration, centrifuging, and pressing or squeezing.

Another common process of liquid removal is that of absorption. Absorption can be considered as a bulk process. If one material absorbs another, the latter permeates or occupies fully the entire bulk of the former. A clear example of this process is the removal of moisture from a material by $CaCl_2$ in a desiccator.

A recently developed method of water removal utilizes the principle of solid sublimation. The material is frozen, and the water removed from it by the sublimation of ice at extremely low pressures.

Fundamentally, drying involves a process of adding heat to a material in order to vaporize liquid that it holds in chemical or mechanical bond. This heat is furnished by one of the following means: radiant energy heating (infra-red), high frequency induction, and exposure to heated and conditioned air. Heat transfer is accomplished by the simultaneous mechanism of radiation, convection, and conduction. Drying with conditioned air is virtually the only method employed in large scale commercial applications. This method has proved to be the most

efficient and economical process for drying in unit operations. Infra-red and induction drying work has almost entirely been limited to single kernel or shallow layer depths. In addition, these processes also exhibit a surface or case hardening effect which cannot be tolerated in the majority of the commercial applications.

Importance of Drying as a Unit Operation

Drying is practiced in a wide variety of industries for a number of different reasons, such as:

1. To prepare a material for process of manufacture which requires conditions obtained only when the material is free of all or part of its moisture.
2. To remove moisture added in previous manufacturing operations.
3. To lessen storage, packing, or transportation costs by removing the unnecessary constituent, water.
4. To preserve material from physical or chemical changes induced or supported by the presence of excess moisture.
5. To bring the product to the standard commercial regain or moisture content upon which basis it is bought or sold.

6. To bring materials to standard moisture contents, necessary when accurate quantities are to be weighed or measured or when materials are to be mixed or packed, since it is very difficult, if not impossible, to mix moist or damp materials uniformly, or to handle such materials automatically, or expeditiously by hand.

It is readily seen that drying processes influence both product quality and value.

In the overall manufacturing operations, the relation of drying time to the operations schedule has a great bearing on the manufacturing costs. In addition, to accomplish adequate drying, a considerable equipment investment is required, since careful and accurate control of the conditions of temperature, humidity, air quantity, and time are required. Finally, since the drying operation is almost always near the end of the product processing an incorrect drying procedure can ruin the product, and the cost of all previous processing is a total loss.

Theories of Drying

A general theory of drying has been established for many substances, and well confirmed with experimental work. However, for many other substances several theories have been proposed, and experimental confirmation is not complete.

In many cases little or no work has been done to establish an explanation for the mechanism of the drying process. The extremely complex geometric structure of many materials presents a difficult problem in mathematical treatment. Perhaps a reasonable first approach would be to group materials of a similar structure. It is likely that substances with a similar structure will have similar drying characteristics. A classification of solid materials according to their structure is given in Figure 1.

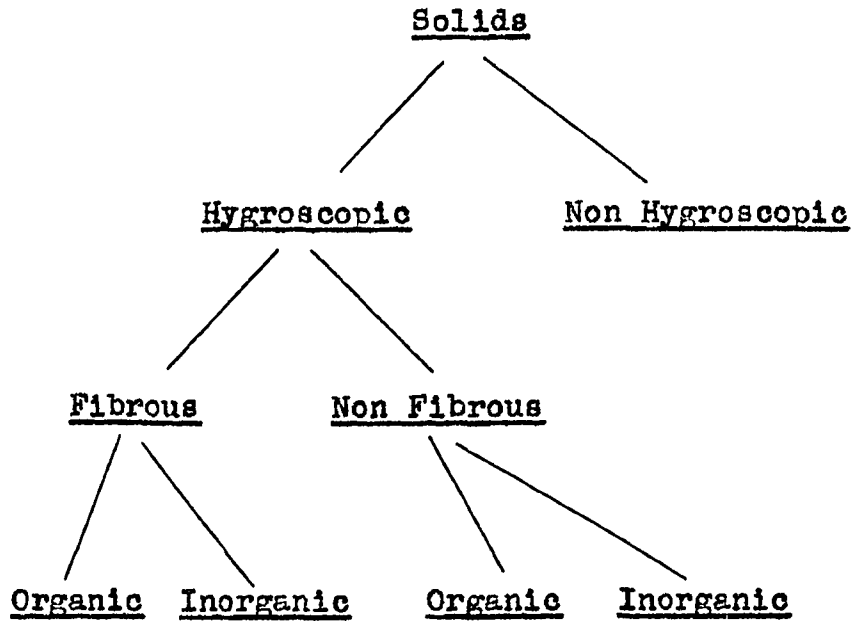


Figure 1

Structural Classification of Solids

This thought cannot be developed as yet because there has not been enough research work done to enable any conclusive correlation. There is evidence, though, that certain groups

of substances exhibit the same drying tendencies. For example, agricultural products (barley, corn, soybeans, rice) seem to behave in essentially the same manner during drying, while cloth, brick clay, and wood are similar, and work done indicates a drying similarity between sand, glass beads, coal, and lead shot. Six general theories on the mechanism of liquid flow in the drying of solids have been proposed; these are:

1. Diffusion
2. Capillary flow
3. Gravity
4. External pressure
5. Convection
6. A sequence of vaporization condensation phenomena induced by a temperature difference

These theories will be discussed in detail.

Drying schedule

A convenient method of presenting the results of a drying experiment is to plot the moisture content against time. Moisture content is often referred to as the percent moisture, or as a concentration. Moisture concentration (C) is defined as the mass of water present in a unit mass of dry solid. Thus, it is seen that C is dimensionless according to the definition. The concentration is also often defined as the mass of water present per unit volume of dry solid, with corresponding dimensions of M/L^3.

An illustration of a typical drying schedule is shown in Figure 2, while another possible schedule is presented in Figure 3.

The first stage of drying, called the warm up period, is an initial adjustment period, in which the material being dried is brought to the equilibrium temperature it assumes with the drying medium.

In the constant rate period the drying surface is completely wetted, and moisture is evaporated at a uniform and constant rate. During the constant rate drying, moisture is removed at the maximum rate during the process.

A falling rate period occurs next, while the drying rate gradually decreases. This decrease involves a linear or more complex function of falling off with time. During the falling rate period portions of the drying surface are dry, hence the drying rate is dependent upon the nature of moisture movement from within the material to the surface.

Critical moisture content is defined as the concentration at which the transition from the constant rate to a falling rate period occurs.

Equilibrium moisture content is the lowest moisture content to which a material may be dried with a given condition of air temperature and humidity. For a material gaining moisture, the equilibrium moisture content is the highest moisture content obtainable for a given air temperature and humidity.

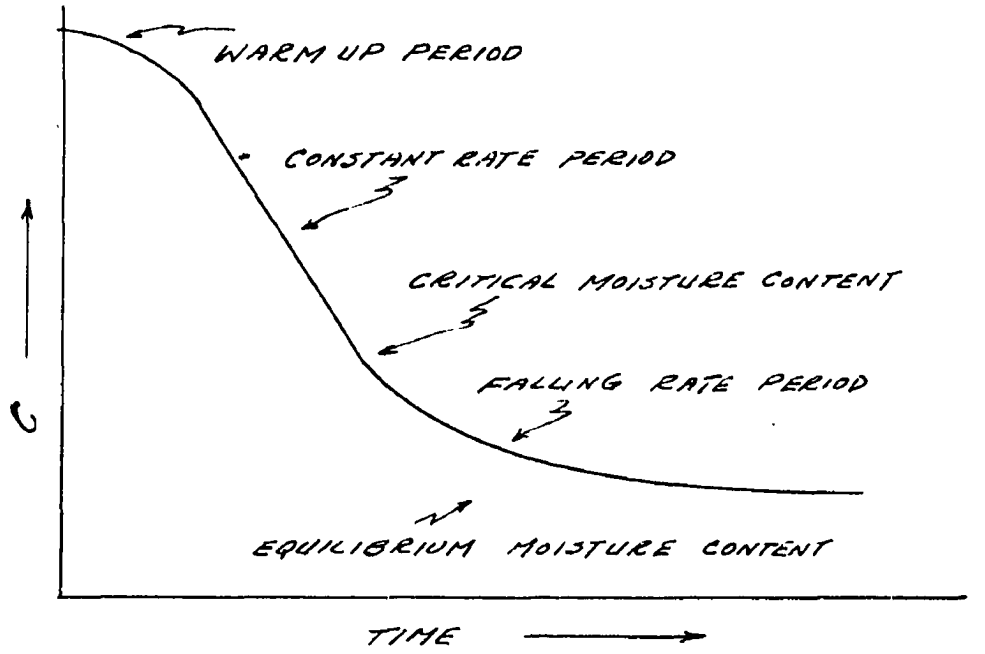


FIGURE 2

GENERAL DRYING SCHEDULE

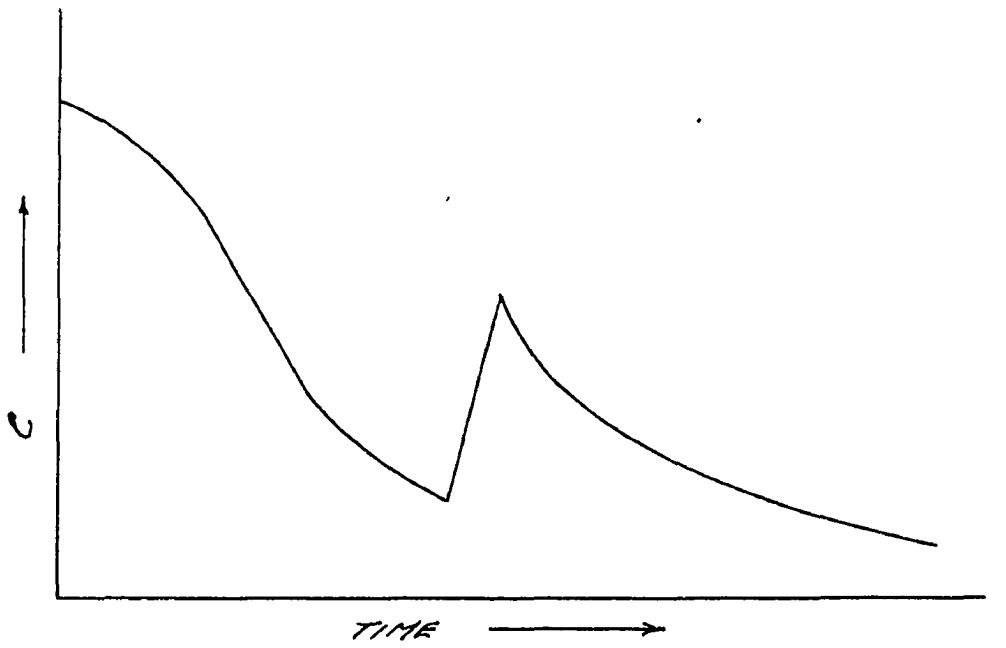


FIGURE 3

GENERAL DRYING SCHEDULE

All materials exhibit a drying schedule similar to the general case discussed, or follow a portion of the general case. Some materials dry with several falling rate periods, or the schedule may have a marked discontinuity as illustrated in Figure 3. In this case, the discontinuity could be caused by a surface cracking, thus increasing the surface area and consequently the rate of drying.

Constant rate period

Sherwood and Comings (1) have shown that during the constant rate period the rate of drying is practically equivalent to the rate of evaporation from a free water surface. Thus, it is reasonable to assume that the constant rate drying is influenced by the same factors that affect the evaporation of water from a free water surface. These factors are the air velocity, temperature, and humidity. In fact, Sherwood (2) presents the following expression for the evaporation of water during the constant rate period (for the velocity range 300 to 1400 fpm):

$$\frac{dW}{Ad\theta} = 0.0083\ V^{0.8}(P_s - P_a) \qquad (1)$$

where

$\frac{dW}{Ad\theta}$ = Evaporation rate (lb/sq ft hr)

V = Air stream velocity parallel to wet surface (fpm)

P_s = Vapor pressure of water at liquid surface temperature (atm)

P_a = Partial pressure of water in the air (atm)

The air stream serves a twofold purpose in drying, providing a carrying medium in moisture removal, and in furnishing a source of heat to evaporate water from the surface. Thus, it can be seen that the constant rate drying is essentially a heat and mass transfer problem. The rate of drying will increase as the rate of heat transmission increases, and as the rate of vapor removal is increased.

Transfer of heat from air to a solid is by convection, conduction, and radiation. Conduction is the predominating mechanism. Convection occurs in the moving air stream, while conduction is through a stagnant viscous film of air at the solid-air interface. The principal resistance to the flow of heat is due to this film. The rate of heat transfer is inversely proportional to the film thickness, so any factor that tends to increase the film thickness, decreases the flow of heat through the film. The heat flow may be expressed as:

$$Q = h_c A(T_a - T_s) \qquad (2)$$

where

Q = Heat flow (Btu/hr)

h_c = Film coefficient (Btu/hr sq ft ^oF)

T_a = Air temperature (^oF)

T_s = Solid surface temperature (^oF)

A = Cross sectional area (sq ft)

So it can readily be seen that any increase in air velocity will decrease the film thickness and increase h_c.

The problem of mass transfer to the air is quite analogous to the heat flow situation. Here problems of resistance to mass transfer are met, and most of the resistance occurs in some film. The mechanism by which water vapor passes through the film is diffusion. The time required for mass transfer varies as the square of the film thickness. Again, an increase in air velocity will decrease the film thickness and increase the rate of mass transfer.

An examination of equation (2) reveals that an increase in the air temperature (T_a) will increase the heat transfer. However, in most cases the upper air temperature limit is fixed by the physical conditions of the drying problem. For example, too high a temperature may cause case hardening of the material. In drying corn, it is believed that temperatures in excess of 165°F will influence the ease in milling of the product.

Humidity of the air stream affects the mass transfer, since it alters the potential or driving force in the mass transfer. The potential causing a transfer of vapors is the difference in vapor pressure of the material flowing through a film. That is, the partial pressure of the water in the air contacting the drying surface and the vapor pressure of the surface water (corresponding to the surface temperature). Flow will occur from the higher vapor pressure to the lower vapor pressure. The moisture concentration in the air (a measure of the humidity) and barometric pressure determine the partial

pressure of the water in the air. It will be shown in the section on psychrometric relations that the partial pressure of water in air is:

$$P_w = \left(\frac{n_w}{n_a + n_w}\right) P$$

where

P_w = Partial pressure of water in air

P = Barometric pressure

n_w = Moles of water in the air

n_a = Moles of dry air

Thus, any increase in the water concentration in air increases the partial pressure of water in the air. Marshall (3) presents the following equation for the rate of moisture transferred through a surface film:

$$\frac{dW}{d\theta} = K\ A\ (P_s - P_w) \qquad (3)$$

where

$\frac{dW}{d\theta}$ = Rate of mass transfer (lb/hr)

K = Mass transfer coefficient (1/hr)

A = Cross sectional area perpendicular to the direction of flow (sq ft)

P_s = Vapor pressure of water at surface temperature (psf)

P_w = Partial pressure of water in air (psf)

In order for drying to occur, the partial pressure of water in the air must be lower than the vapor pressure of

water on the solid surface. Thus, the rate of drying increases as the water vapor concentration in the air is decreased.

Radiation heat transfer also is present during drying, with the effect of raising the material temperature above a theoretically predicted value. During the constant rate period, the surface in the absence of radiation assumes a temperature equal to the wet bulb temperature of the air. However, if the surface receives radiant energy it will assume a temperature above the wet bulb temperature. Another effect is the heat conducted through metal containing walls, which tends to increase the drying rate. Marshall (3) suggests the following equation for the duration of the constant rate period:

$$\theta = \frac{W(T_a - T_s)\, h_{fgs}}{A\left[h_c(T_a - T_s) + h_r(T' - T_s)\right]} \qquad (4)$$

where

θ_c = Constant rate period time

W = Mass of water removed

h_{fgs} = Latent heat of vaporization of water at the surface temperature ✓

h_r = Radiation heat transmission coefficient

T' = Radiating source temperature

and the remaining terms defined as in equation (2).

Falling rate period

Newman (4) states that the falling rate period commences

when the water film covering the microscopic surface particles becomes so thin that further drying will rupture it, leaving small dry areas - therefore decreasing the wetted area and consequently decreasing the rate of drying. Then the rate of drying will be influenced by the surface condition and the mechanism of moisture movement from within the material to the surface. At any instant the rate of drying is a function of the relation of the surface and drying medium. Thus, the falling rate period is an unsteady state condition related to the nature of material being dried, its geometry, as well as the air temperature, humidity, and to a lesser extent the velocity. As previously mentioned, there are several theories concerning the moisture flow during this period, and each will be discussed in detail.

Diffusion

Diffusion consists in a redistribution of molecules within a single phase, brought about by molecular motion of translation and mutual bombardment. The diffusion process may be readily visualized by the phenomenon of one gas diffusing into another to form a single gas mixture. The diffusion of a liquid follows Fick's law:

$$P = - K A \left(\frac{\partial \sigma}{\partial x} \right) \qquad (5)$$

where

P = Rate of permeation

K = Diffusion constant

A = Cross sectional area

$\frac{\partial C}{\partial x}$ = Concentration gradient

Then it can be shown that:

$$\frac{\partial C}{\partial t} = D\left[\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right] \qquad (6)$$

where D = diffusivity of material (L^2/T)

Moisture flow by diffusion may then be found by integrating equation (6) with suitable boundary conditions. Sherwood (5) and Newman (6) present solutions for this equation in the drying of slabs, cylinders, and spheres.

However, in order that moisture be transferred in a solid by true diffusion the following conditions must be met:

(a) The diffusivity D for the material must be constant

(b) The material must be isotropic and homogeneous

(c) Drying must be accomplished without shrinkage

Hougen and McCauley (7) point out that the mechanism of diffusion is restricted to equilibrium moisture contents below the point of atmospheric saturation, and to single phase solid systems in which the water and solid are mutually soluble. In the same article Hougen and McCauley show that diffusion occurs in the drying of soaps, glues, gelatins, and pastes, as well as in the last stages of drying clays, starches, flour, textiles, paper and wood. It is further suggested in this article that the

diffusion equation may be modified with a variable diffusivity (D). The diffusivity may be a function of moisture concentration, temperature, pressure, and density.

Smith (8) has presented evidence of diffusion controlling the drying of seed corn.

Capillary flow

Capillarity is the flow of a liquid through interstices and over the surface of a solid due to molecular attraction between the liquid and the solid. When a force acts between the molecules of a solid and liquid to produce wetting, it is called adhesion tension. The unbalanced force of attraction of the molecules of a liquid at its surface in contact with a vapor or gas is called surface tension. Surface wetting may be caused by adhesion tension, while surface tension causes the liquid subsequently to flow in reducing its interfacial area with the gas or vapor with which it is in contact. A porous body which exhibits the property of capillarity is said to be in a capillary state when it is saturated with water. An example of capillary flow, or capillary suction, is the mechanism of the rise of kerosene in a wick. Capillary suction requires small pores, and a surface wetted with liquid. The moisture movement is due to surface tension of the liquid, and may be measured with a capillary tube according to:

$$\sigma = \frac{rhg\rho}{2} \qquad (7)$$

where

δ = Capillary suction

r = Radius of tube

h = Height of tube

ρ = Density of liquid

g = Gravitational constant

In the moisture movement during drying, the material may be viewed as containing a bundle of capillary tubes. The rate of drying is dependent upon the size of the pores or interstices and their distribution within the material.

Gravity

In this theory, the force of gravity tends to pull water to the bottom of a solid. Gravity acts only vertically. In contrast, diffusion acts in the direction of decreasing concentration, and capillary flow is dependent upon the size and distribution of the intersticial pores.

Convection

This is a movement of moisture induced by convection which occurs within a solid because of a temperature gradient. This process is called the Soret effect and is often termed thermodiffusion. Flow is in the direction of decreasing temperature.

Porous flow theory

Marshall (3) proposes a porous flow theory in which

moisture flow is attributed to the combined effect of capillary suction, external pressure, and gravity. It is assumed that the rate of flow at any point is proportional to the moisture density gradient. Accordingly:

$$\frac{\rho}{1+v}\frac{\partial v}{\partial T} = \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} + \frac{\partial^2 \phi}{\partial z^2} \qquad (8)$$

where v = water concentration (mass water/mass DS).

Vaporization condensation theory

In this theory, temperature differences are believed to cause vapor pressure gradients within a solid, which results in evaporation of the liquid and its subsequent condensation on a colder surface. Hence, when a wet solid is heated at its bottom surface and dry air is circulated over the top, vaporization may occur at the bottom where the temperature is the highest, and the vapor diffusing upward may be repeatedly condensed and vaporized before finally escaping as vapor into the air. If heated to the boiling point, the entire column of liquid may be moved upward.

PSYCHROMETRIC RELATIONS

Psychrometry is the study of the behavior of dry air - water vapor mixtures.

In air drying, the air stream provides the heat necessary for evaporation and serves as a vehicle to carry away the moisture evaporated. The properties of the air stream are, therefore, of principal importance in drying applications, and it is desirable to review briefly the various terms and quantities used in air conditioning calculations.

Perfect Mixtures

The relationships between the properties of the components of a mixture of gases and vapors and the total mixture properties are based upon the Gibbs-Dalton Law. Two principles deduced from the law are stated as:

(a) The total pressure of a gaseous mixture is equal to the sum of the pressures that each component gas would assume individually at the temperature of the mixture and total volume of the mixture.

(b) The total enthalpy of a gaseous mixture is equal to the sum of the enthalpies of each component gas individually at the temperature of the mixture and total volume of the mixture.

Although these principles have been long regarded as fundamental, experience indicates that they are not strictly true for all mixtures of gases and vapors. It is apparent that a mixture of gases can obey these principles only if the gases are mixed with no accompanying heat effect, and the resultant mixture has no intermolecular activity. Mixtures of gases and vapors that strictly obey the Gibbs-Dalton principles are called perfect mixtures.

Experience has shown that actual gas mixtures behave quite closely to perfect mixture behavior at ordinary atmospheric pressures. It should be noted that a mixture of gases and vapors need not follow perfect gas behavior to be a perfect mixture, and in general, gases will behave as a perfect mixture through a wider range of conditions than the gases will behave as a perfect gas. Therefore, assuming perfect mixture behavior is less restrictive than assuming perfect gas behavior.

Moist air is essentially a perfect mixture of dry air and water vapor. In addition, dry air at normal atmospheric pressure may be assumed a perfect gas, while water vapor acts as a perfect gas at very low pressures.

Partial pressures

The partial pressure of a component gas in a mixture of gases is defined as the pressure that the gas would exert alone when occupying the volume of the mixture at the temperature of the mixture. Then, for perfect mixtures, the total pressure of

a gaseous mixture equals the sum of the partial pressures of its component gases.

Considering moist air as a mixture of dry air and water vapor, the following characteristic equations follow from the definitions of the perfect gas and perfect mixture:

$$P = P_a + P_w$$

$$n = n_a + n_w$$

$$P_a V = n_a RT$$

$$P_w V = n_w RT$$

$$\frac{P_w}{P} = \frac{n_w}{n}$$

$$\frac{P_a}{P} = \frac{n_a}{n}$$

where

P = Barometric pressure

P_a = Partial pressure of dry air

P_w = Partial pressure of water vapor

n = Moles of moist air

n_a = Moles of dry air

n_w = Moles of water vapor

V = Volume of moist air

T = Absolute temperature of moist air

R = Gas constant (1545 ft lb/mole ^{o}F)

Humidity

Humidity is a general term used to express the water vapor concentration in a quantity of dry air or wet mixture. Specific humidity (W) is defined as the pounds of water present per pound of dry air, thus:

$$W = \frac{M_w}{M_a} \tag{9}$$

Dew point

The dew point of a mixture is the temperature at which water vapor begins to condense when the mixture is cooled at constant pressure. Thus, the dew point of a mixture is the saturation temperature corresponding to the partial pressure of the water vapor in the mixture. Air at the dew point temperature is said to be saturated.

Adiabatic saturation

An expression for the specific humidity of moist air is derived from an energy balance for the adiabatic saturation of the air. Consider air flowing over an exposed liquid surface in a completely insulated duct, as illustrated in Figure 4. Air at temperature T_1 comes in contact with a surface of liquid water at a lower temperature T_s with a corresponding vapor pressure of P_s, sufficient water vapor is evaporated adiabatical-

ly from the liquid surface so that the air mixture leaves saturated at temperature T_s. It is apparent from a material balance of the process that the weight of water evaporated is equal to $M_a(W_s - W_1)$.

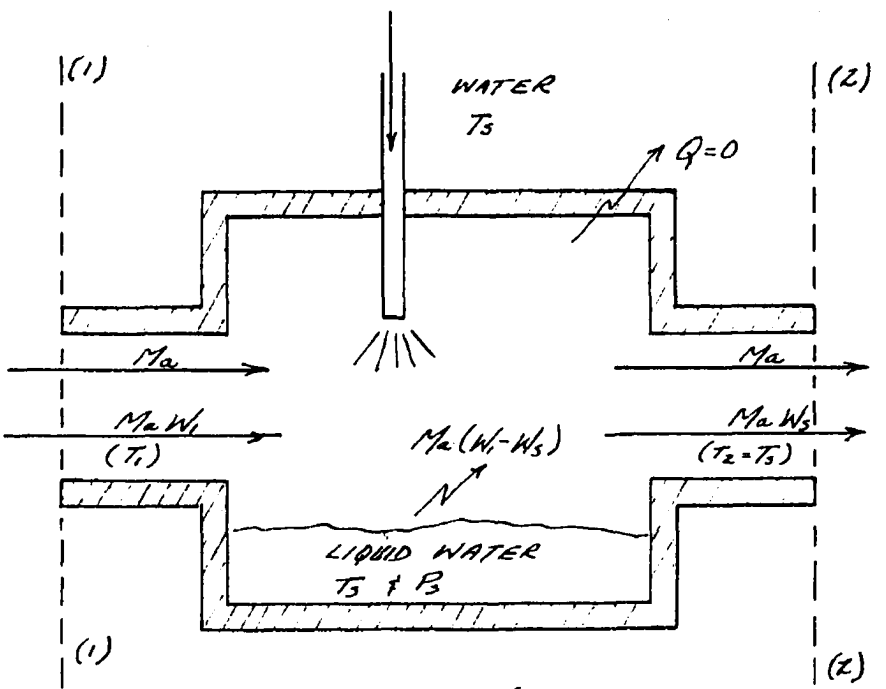


FIGURE 4

ADIABATIC SATURATION OF AIR

According to the steady flow energy balance of the process:

$$M_a h_{a1} + M_a W_1 h_{w1} + M_a (W_1 - W_s) h_{ws} = M_a h_{as} + M_a W_s h_{w2}$$

and

$$h_{a1} - h_{as} = C_p (T_1 - T_s) = 0.241 (T_1 - T_s)$$

$h_{w1} = h_g$ at $T_1 = h_{g1}$ (neglecting any change of enthalpy with pressure at T_1)

$h_{w2} = h_g$ at $T_s = h_{gs}$

$h_{ws} = h_f$ at $T_s = h_{fs}$

$$h_{w2} - h_{ws} = h_{gs} - h_{fs} = h_{fgs} \quad (h_{fg} \text{ at } T_s)$$

so

$$W_1 = \frac{W_s \, h_{fgs} - (0.241)(T_1 - T_s)}{h_{g1} - h_{fs}} \tag{10}$$

Here, W_1 is the specific humidity of the entrant air at T_1 while W_s is the specific humidity of air saturated at T_s, called the adiabatic wet bulb temperature.

According to the partial properties of a mixture:

$$\frac{P_w}{P_a} = \frac{n_w}{n_a}$$

$$W = \frac{(n_w)(18)}{(n_a)(29)} = 0.622 \, \frac{n_w}{n_a}$$

Thus:

$$W_s = 0.622 \left(\frac{P_s}{P_1 - P_s} \right) \tag{11}$$

Wet and dry bulb temperatures

The most common method of determining direct psychrometric quantities employs a psychrometer or wet and dry bulb thermometer. This instrument comprises two thermometers, one of which has its bulb covered with a moistened wick. When the psychrometer is brought into contact with a moving stream of wet mixture, the dry bulb indicates the mixture temperature, called the dry bulb temperature. The wet bulb thermometer indicates the temperature of the liquid surface of the wick, called the wet bulb temperature.

It has been shown that for air-water vapor mixtures, the psychrometer is entirely analogous to the adiabatic saturation apparatus discussed. Accordingly, the dry bulb temperature is analogous to T_1 and the wet bulb temperature is virtually the same as the adiabatic wet bulb temperature, T_s. Thus, the specific humidity of air may be determined with the use of the psychrometer and the application of equation (10), substituting the dry bulb temperature for T_1 and the wet bulb temperature for T_s, with P_1 as the barometric pressure and the other values taken from the steam tables.

The wet bulb temperature equals the dry bulb temperature and the dew point in a saturated mixture.

The Psychrometric Chart

It has been shown that the specific humidity W_1 is a function of the barometric pressure P, dry bulb temperature T_1, wet bulb temperature T_s, and steam table properties. The psychrometric chart is a graphical representation of the adiabatic saturation equation (10) with specific humidity - enthalpy coordinates, W is plotted against wet and dry bulb temperatures at standard pressure. Obviously, the use of the chart is limited in use to cases of only standard pressure.

Barometric pressure correction for standard pressure psychrometric chart

It is possible to evolve a pressure correction factor to apply to a specific humidity taken from a standard pressure chart. Considering W_1 as the humidity of air at T_1 and T_{s1}, and P_1 = standard pressure (29.92 in. Hg), and W_2 the humidity for air at the same wet and dry bulb temperature but $P_2 \neq P_1$. Then, let $W_1 - W_2 = Y$, where Y is, in fact, the difference between the specific humidity of air at a given condition of temperature and pressure and the specific humidity for the given temperature taken from a standard pressure psychrometric chart. Since:

$$W_1 = \frac{0.622 \left(\frac{P_{s1}}{P_1 - P_{s1}}\right) h_{fgs1} - 0.241 (T_1 - T_{s1})}{h_{g1} - h_{fs1}}$$

$$W_2 = \frac{0.622 \left(\frac{P_{s2}}{P_2 - P_{s2}}\right) h_{fgs2} - 0.241 (T_2 - T_{s2})}{h_{g2} - h_{fs2}}$$

and:

$$T_1 = T_2$$

$$T_{s1} = T_{s2}$$

$$h_{g1} = h_{g2}$$

$$h_{fs1} = h_{fs2}$$

$$h_{fgs1} = h_{fgs2}$$

$$P_{s1} = P_{s2}$$

$$P_1 = 29.92 \text{ in. Hg} \neq P_2$$

it follows that:

$$Y = \frac{0.622\left[\left(\frac{P_{s1}}{P_2 - P_{s1}}\right) - \left(\frac{P_{s1}}{P_2 - P_{s1}}\right)\right] h_{fgs1}}{h_{g1} - h_{fs1}}$$

or:

$$Y = \left(\frac{P_2 - P_1}{P_2 - P_{s1}}\right)\left(\frac{0.622\ P_{s1}}{P_1 - P_{s1}}\right)\left(\frac{h_{fgs1}}{h_{g1} - h_{fs1}}\right)$$

Now, let Z, to be called a pressure correction factor, be defined as the dimensionless term:

$$Z = \left(\frac{0.622\ P_{s1}}{P_1 - P_{s1}}\right)\left(\frac{h_{fgs1}}{h_{g1} - h_{fs1}}\right)$$

or in general:

$$Z = \left(\frac{0.622\ P_s}{P - P_s}\right)\left(\frac{h_{fgs}}{h_g - h_{fs}}\right) \qquad (12)$$

where P is standard pressure and the subscript s refers to vapor

pressures and enthalpies at the wet bulb temperature, while h_g is the enthalpy of water vapor at the dry bulb temperature. Now:

$$Y = Z\left(\frac{P_2 - P_1}{P_2 - P_s}\right)$$

and:

$$W_2 = W_1 - Y$$

So:

$$W_2 = W_1 - Z\left(\frac{P_2 - P_1}{P_2 - P_s}\right) \qquad (13)$$

An examination of the equation for Z reveals that the quantity $(0.622\ \frac{P_s}{P - P_s})$ depends entirely upon the wet bulb temperature, and the quantity $(\frac{h_{fgs}}{h_g - h_{fs}})$ is virtually constant for a given wet bulb temperature, since only h_g varies with the dry bulb temperature. However, in the normal psychrometric range the variation of h_g is a negligible amount compared to the magnitude of h_{fgs}. Therefore, Z is plotted in Figure 5 as a function of the wet bulb temperature. A table of values for Z over a wider range of temperatures is included in the Appendix as Table 1.

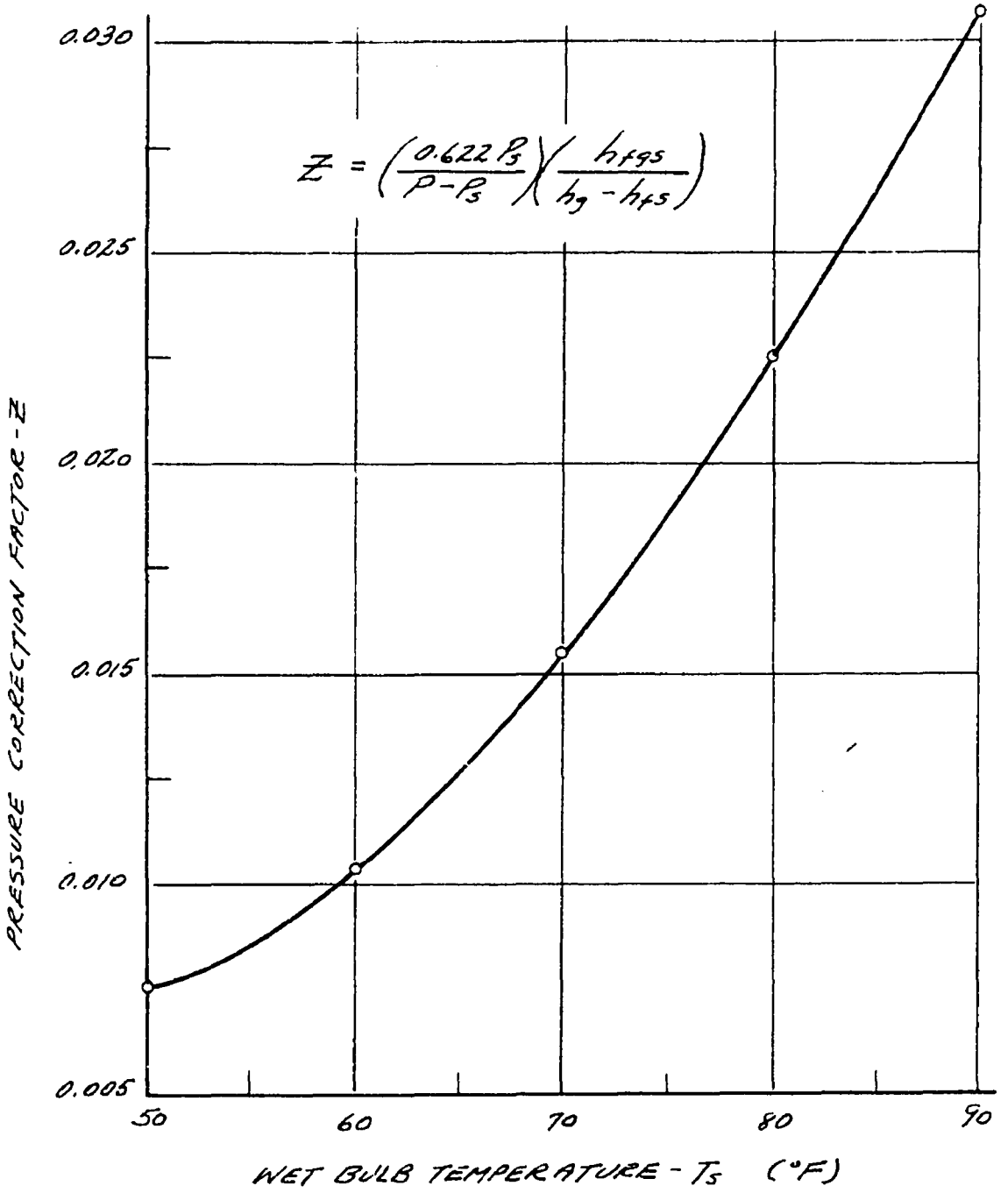


FIGURE 5

VARIATION OF PRESSURE CORRECTION FACTOR WITH WET BULB TEMPERATURE

THEORETICAL DEVELOPMENT

The purpose of this investigation is to derive an equation defining the mechanism for the drying of organic granular solids. Experimental phases of the investigation are confined to the drying of soybeans and shelled corn. The problem may be attacked either from the standpoint of dimensional analysis or a solution of the basic differential equation based on pertinent assumptions. Both of these methods will be used in this study. A complete solution will be made for the soybeans, and the similarity in drying of corn and soybeans will be studied.

Dimensional Analysis

The general factors involved in drying are the geometry and physical properties of the material, and the properties of the drying medium. Since this thesis will be concerned with the air drying of solids, the properties of the air supplied are pertinent.

Spherical symmetry is assumed for the soybean, hence its geometry may be described by the radius of the bean. A corn kernel is approximately a slab with the shape of a segment of a circle, hence for this study the geometry of the corn is described by considering the corn to have an equivalent radius.

The equivalent radius of the corn is defined as the radius of a sphere having a surface area equivalent to the surface area of the corn kernel.

The property of the material that has a bearing on the drying characteristics of the substance is its diffusivity, since diffusivity is an index of the moisture transfer and storage properties of a substance.

The properties of the air controlling moisture pick-up are assumed to be temperature, humidity and velocity. Humidity may be accounted for by considering the partial pressure of the water in the air. Partial pressure of water in air corresponds to the dew point temperature of the air. The air temperature influences the temperature of the water evaporated from the surface of the material. Initially, with the bean saturated, the surface water temperature will approximate the wet bulb temperature of the air. Thus, the surface water temperature will vary between the wet and dry bulb temperatures of the air during the course of the drying. Now, the driving force in the moisture removal is the difference in vapor pressure between the water in the air and the surface moisture. Vapor pressures of water at the surface will vary as the temperature changes. Therefore, the vapor pressure of the surface water will be assumed to be the mean of the pressures corresponding to the dry and wet bulb temperatures of the air. This mean vapor pressure of the surface water will be identified as P_{sm}, and

the partial pressure of water in the air as P_w. The driving force in the moisture removal then is dependent upon $P_{sm} - P_w$. Barometric pressure (P) will also be considered as a variable. However, the barometric pressure is not an independent quantity, since it is related to the partial pressure of the water in the air by the expression:

$$P_w = \left(\frac{n_w}{n_w + n_a} \right) P$$

Next, the variables are enumerated and their dimensions determined. The following list of quantities are assumed to have a bearing on the drying of the corn and soybeans with air:

Variable	Symbol	Dimensions
Average moisture concentration	C_a	--
Time	t	T
Partial pressure of water in air	P_w	F/L^2
Mean vapor pressure of surface water	P_{sm}	F/L^2
Barometric pressure	P	F/L^2
Diffusivity of material	D	L^2/T
Air velocity	V	L/T
Radius of soybean	R	L
Equivalent radius of corn	R_e	L
Factor for corn	F	--

The corn F factor is a term that relates the corn drying properties to those of the soybeans. Thus, the F factor in-

volves both the shape and composition of the corn kernel.

For the soybeans, there are 7 independent variables and 3 primary dimensions. According to the Buckingham P_i theorem, 4(=7-3) independent dimensionless groups are required in a mathematical expression of the phenomenon. Those groups, commonly called P_i terms, may be:

$$\pi_1 = C_a$$

$$\pi_2 = \frac{Dt}{R^2}$$

$$\pi_3 = \frac{Vt}{R}$$

$$\pi_4 = \frac{P_{sm}-P_w}{P}$$

Hence:

$$C_a = f\left[\frac{Dt}{R^2}, \frac{Vt}{R}, \frac{P_{sm}-P_w}{P}\right] \qquad (14)$$

For the corn, there are 8 independent variables and 3 dimensions, so 5 dimensionless groups are required. These P_i terms may be:

$$\pi_1 = C_a$$

$$\pi_2 = \frac{Dt}{R_e^2}$$

$$\pi_3 = \frac{Vt}{R_e}$$

$$\pi_4 = \frac{P_{sm}-P_w}{P}$$

$$\pi_5 = F$$

Hence:

$$C_a = f\left[\frac{Dt}{R_e 2}, \frac{Vt}{R_e}, \frac{P_{sm}-P_w}{P}, F\right] \qquad (15)$$

Equations (14) and (15) indicate the grouping of quantities involved in the drying problem. In order to determine a reasonable method of combining these terms to form a reliable prediction equation, an analytical evaluation of the drying process would be helpful. Therefore, an equation defining the drying process will be developed.

Analytical Analysis

Experimental drying of barley, soybeans, and corn has shown the drying is all at a falling rate. In addition, it appears that the drying rate is dependent upon the diffusion of moisture from within to the outside of the material. Initially, it will be assumed that the moisture movement during the drying will be by diffusion.

The fundamental diffusion mechanism follows Fick's law for the steady state:

$$P = - KA\left(\frac{\partial C}{\partial x}\right) \qquad (16)$$

where: P = Rate of permeation (M/T)

K = Diffusion constant (M/LT)

A = Area (L^2)

$\frac{\partial C}{\partial x}$ = Concentration gradient (1/L)

C = Moisture concentration ($\frac{\text{Mass } H_2O}{\text{Mass DS}}$)

For the case of unsteady state diffusion, consider the flow through an element of volume with a unit cross section as indicated in Figure 6. Moisture accumulation in the element of volume is found by subtracting the flow out of the element from the flow into the element, thus:

$$P_1 - P_2 = -K\left(\frac{\partial C}{\partial x}\right) + K\frac{\partial}{\partial x}\left[C + \left(\frac{\partial C}{\partial x}\right) dx\right]$$

and:

$$P_1 - P_2 = K\frac{\partial^2 C}{\partial x^2} dx \qquad (17)$$

also:

$$P_1 - P_2 = a\frac{\partial C}{\partial t} dx \qquad (18)$$

where: a = a constant (M/L^3) depending upon the moisture storing capacity of the material

t = time

By combining equations (17) and (18):

$$\frac{\partial C}{\partial t} = \frac{K}{a}\frac{\partial^2 C}{\partial x^2}$$

will result.

Now, let $D = K/a$

where: D = Diffusibility of material (L^2/T)

So:

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial x^2} \qquad (19)$$

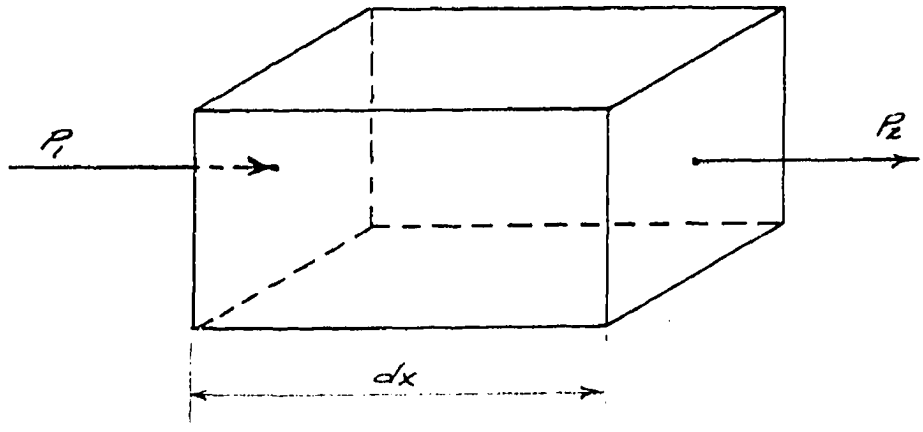


FIGURE 6

PERMEATION - ELEMENT OF VOLUME

Where P_1 = Rate of permeation of moisture through one face of the element

P_2 = Rate of permeation of moisture through the opposite face of the element

dx = Distance between the two faces of the element

Volume of element = dx

This result may be extended by a similar line of reasoning for three dimensional flow. If the material is isotropic:

$$\frac{\partial C}{\partial t} = D\left(\frac{\partial^2 C}{\partial x^2} + \frac{\partial^2 C}{\partial y^2} + \frac{\partial^2 C}{\partial z^2}\right) = D\nabla^2 C \qquad (20)$$

For the particular case of the soybean, it is assumed that the bean is a homogeneous mass with spherical symmetry. Changing the variable to the radius of the soybean, r, equation (20) may be written as:

$$\nabla^2 C = \frac{\partial^2 C}{\partial r^2} + \frac{2}{r}\frac{\partial C}{\partial r} \qquad (21)$$

and:

$$\frac{\partial C}{\partial t} = D\left[\frac{\partial^2 C}{\partial r^2} + \frac{2}{r}\frac{\partial C}{\partial r}\right] \qquad (22)$$

Let:

$$u = Cr$$

and

$$\frac{\partial u}{\partial r} = C + r\frac{\partial C}{\partial r}$$

$$\frac{\partial^2 u}{\partial r^2} = r\frac{\partial^2 C}{\partial r^2} + 2\frac{\partial C}{\partial r}$$

since:

$$\frac{\partial C}{\partial t} = \frac{D}{r}\frac{\partial^2 u}{\partial r^2}$$

it follows that:

$$\frac{\partial u}{\partial t} = D\frac{\partial^2 u}{\partial r^2} \qquad (23)$$

A solution for equation (23) may be obtained by integrating the equation and taking into account suitable boundary conditions for the problem. The boundary conditions will be assumed as:

$C = f(r)$ when $t = 0$ for all r

$C = 0$ when $r = R$ for all t

where R is the radius of the sphere.

Moisture concentration C is the concentration at any point in the sphere for all values of t. The condition $C = 0$ at the external surface implies that the moisture distribution within the solid decreases to a value of zero at the outside surface. Thus, it is assumed that regardless of the moisture distribution in the solid at the external surface the concentration drops to zero an infinitesimal distance from the surface.

But: $u = Cr$

so:
1. $u = rf(r)$ when $t = 0$ for all r
2. $u = 0$ when $r = R$ for all t
3. $u = 0$ when $r = 0$ for all t

Now, assuming that the variables are separable, and that u varies with r and t, a solution to equation (23) may be assumed of the form:

$$u = X(r)\,T(t)$$

where:

$X(r)$ is a function of r

$T(t)$ is a function of t

it follows that:

$$X(r)\ T'(t) = DX''(r)\ T(t)$$

or:

$$\frac{X''(r)}{X(r)} = \frac{T'(t)}{DT(t)}$$

Since $\frac{X''(r)}{X(r)}$ can vary only with r, and $\frac{T'(t)}{DT(t)}$ only with t, they must both equal a constant, so:

$$\frac{X''(r)}{X(r)} = a = \frac{T'(t)}{DT(t)}$$

and

$$X''(r) - aX(r) = 0 \qquad (24)$$

$$T'(t) - aDT(t) = 0 \qquad (25)$$

Now, for $u = X(r)\ T(t)$ to satisfy the boundary conditions 2 and 3:

$$X(r) = 0 \quad \text{when } r = 0$$

$$X(r) = 0 \quad \text{when } r = R$$

The equation

$$X''(r) - aX(r) = 0 \qquad (24)$$

is a homogeneous differential equation with constant coefficients, hence:

$$X(r) = Ae^{\sqrt{a}r} + Be^{-\sqrt{a}r}$$

However, if a is positive, this solution does not go to zero when r = 0 or r = R. By assuming a to be negative:

$$a = -b^2$$

the general solution of equation (25) may be taken as:

$$X(r) = M \sin (br) + N \cos (br)$$

when $r = 0$, $N = 0$

and for $r = R$, $X(R) = 0$, $\sin (bR) = 0$

$\sin (bR)$ is equal to zero when:

$$b = \frac{n\pi}{R} \quad \text{for all values of } n.$$

Thus, the solution of equation (24) has the form:

$$X(r) = M \sin \frac{n\pi r}{R} \tag{26}$$

Equation (25) is next considered:

$$T'(t) - aDT(t) = 0$$

and boundary condition 1 will be satisfied when:

$$T(t) = rf(r) \quad \text{for } t = 0$$

The general solution of equation (25) may be taken as:

$$T(t) = Pe^{aDt}$$

but $a = -b^2 = -\frac{n^2\pi^2}{R^2}$

and:

$$T(t) = P(\exp)\left[-\left(\frac{n\pi}{R}\right)^2 Dt\right]$$

where:

$$(\exp)\left[-\left(\frac{n\pi}{R}\right)^2 Dt\right] = e^{-\left(\frac{n\pi}{R}\right)^2 Dt}$$

$$u = B_n \sum (\exp)\left[-\left(\frac{n\pi}{R}\right)^2 Dt\right] \sin \frac{n\pi r}{R} \qquad (27)$$

where the constants B_n are arbitrary.

No sum of finite number of functions (27) can satisfy the non-homogeneous condition that $u = rf(r)$ when $t = 0$ unless $f(r)$ is a linear combination of sines of multiples of r. The infinite series of those functions:

$$u = \sum_1^\infty B_n (\exp)\left[-\left(\frac{n\pi}{R}\right)^2 Dt\right] \sin \frac{n\pi r}{R}$$

will reduce to $rf(r)$ when $t = 0$, provided the coefficients B_n are so determined that:

$$rf(r) = \sum_1^\infty B_n \sin \frac{n\pi r}{R}$$

assuming that the series can be integrated term by term. Hence, the coefficients must have the values:

$$B_n = \frac{2}{R} \int_0^R rf(r) \sin \frac{n\pi r}{R} \, dr \qquad (28)$$

and finally:

$$u = \frac{2}{R} \sum_1^\infty (\exp)\left[-\left(\frac{n\pi}{R}\right)^2 Dt\right] \sin \frac{n\pi r}{R} \int_0^R rf(r) \sin \frac{n\pi r}{R} \, dr$$

since: $u = Cr$

$$C = \frac{2}{Rr} \sum_1^\infty (\exp)\left[-\left(\frac{n\pi}{R}\right)^2 Dt\right] \sin \frac{n\pi r}{R} \int_0^R rf(r) \sin \frac{n\pi r}{R} \, dr \qquad (29)$$

Next, let us assume that the initial moisture distribution may

be represented by an average initial moisture concentration (C_o), so equation (29) reduces to:

$$C = \frac{2C_o}{R_r} \sum_{1}^{\infty} (\exp)-(\frac{n\pi}{R})^2 Dt \sin \frac{n\pi r}{R} \int_o^R r \sin \frac{n\pi r}{R} dr$$

and:

$$C = -\frac{2C_o R}{n\pi r} \sum_{1}^{\infty} (\exp)-(\frac{n\pi}{R})^2 Dt \sin \frac{n\pi r}{R} \cos n\pi \qquad (30)$$

To get an expression for the average value of C (C_a) at any time t, each element of volume is multiplied by its corresponding moisture concentration C and density and such terms summed for the whole sphere; then divided by the product of the volume of the sphere and its density. Then:

$$C_a = \frac{3}{4\pi R^3} \int_o^R C\, 4\pi r^2 dr$$

or:

$$C_a = \frac{3}{R3} \int_o^R - \frac{2RC_o}{n\pi r} \sum_{1}^{\infty} (\exp)-(\frac{n\pi}{R})^2 Dt \sin \frac{n\pi r}{R} \cos n\pi r^2 dr$$

which is integrated as:

$$C_a = \frac{6C_o}{n^2\pi^2} \sum_{1}^{\infty} (\exp)-(\frac{n\pi}{R})^2 Dt$$

and transposing terms:

$$\frac{C_a}{C_o} = \frac{6}{n^2\pi^2} \sum_{1}^{\infty} (\exp)-(\frac{n\pi}{R})^2 Dt \qquad (31)$$

Values for D may now be calculated from experimental drying data. It is apparent that it is advantageous to multiply the second P_i term by a π^2, so:

$$\pi_2 = \frac{\pi^2 Dt}{R^2}$$

Equation (14) will then have the form:

$$C_a = f\left[\frac{\pi^2 Dt}{R^2},\ \frac{Vt}{R},\ \frac{P_{sm}-P_w}{P}\right] \tag{32}$$

In turn, equation (15) is changed to:

$$C_a = f\left[\frac{\pi^2 Dt}{R_e^2},\ \frac{Vt}{R_e},\ \frac{P_{sm}-P_w}{P},\ F\right] \tag{33}$$

An experimental drying program was then established so that D could be determined with the use of equation (31) and the P_i terms of equations (32) and (33) evaluated.

DESCRIPTION OF APPARATUS

The experimental drier and the air conditioning apparatus are located on the north balcony of the Mechanical Engineering laboratory. A schematic layout of the air conditioning equipment is given in Figure 7, and the drying cabinet in Figure 8.

Air Conditioner

The air conditioning equipment is provided with three air intakes; one admits air from the outside, and the other two admit air from the room. Each inlet is provided with an air proportioning damper; thus, any ratio of outside to room air may be maintained. One of the room inlets is located near the exit from the air conditioner. This permits a mixture of room air and conditioned air to be admitted to the system.

Steam humidifier

The horizontal room air intake is fitted with a steam humidifier at the entrance. This steam humidifier is a 1 1/8 inch perforated pipe connected to the main steam supply line. Steam flow to the humidifier is controlled with a globe valve. Piping is arranged so that steam may be used from either the main college supply line or from the Mechanical Engineering laboratory boiler. The boiler steam line includes a pneumatical-

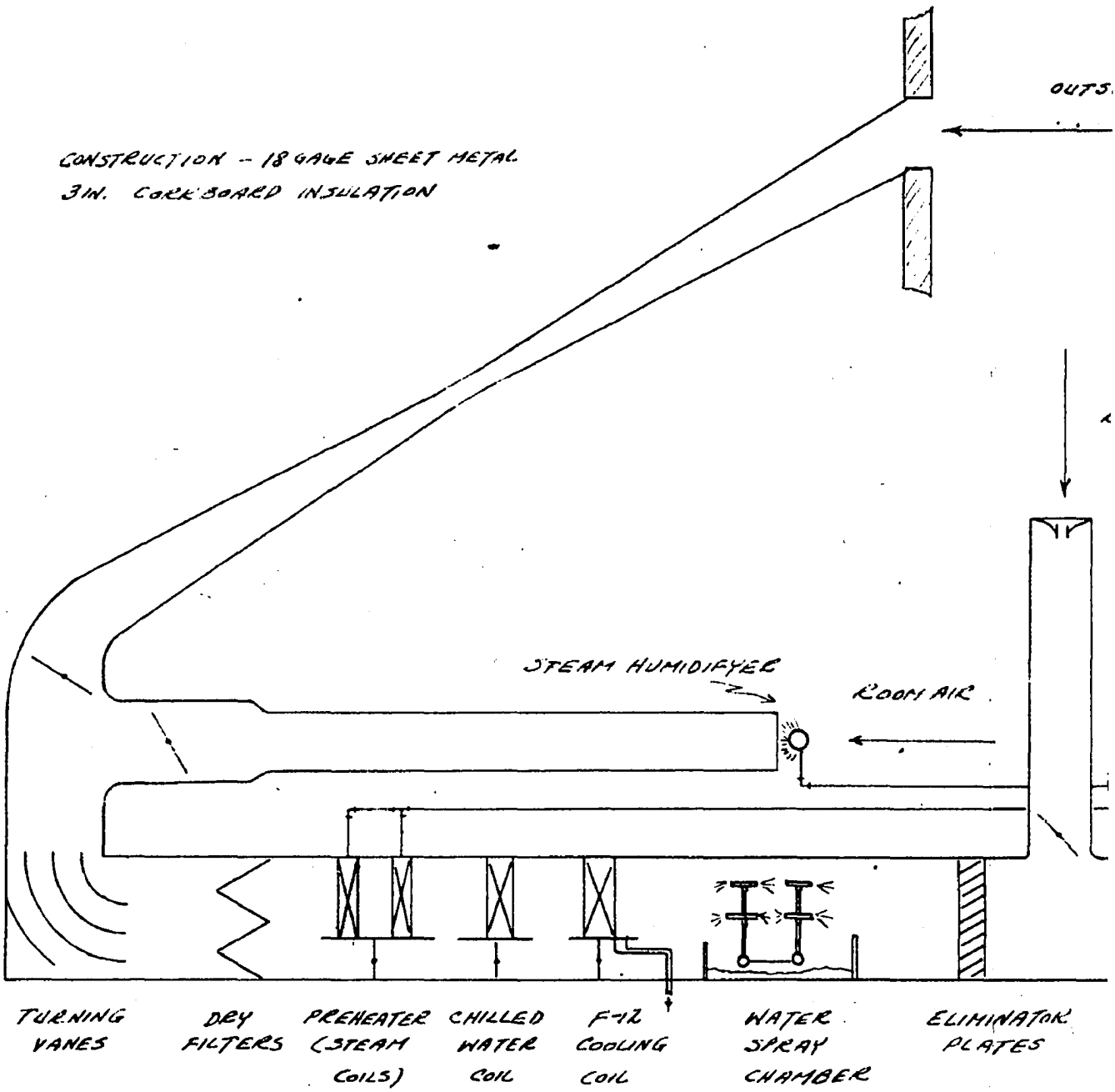
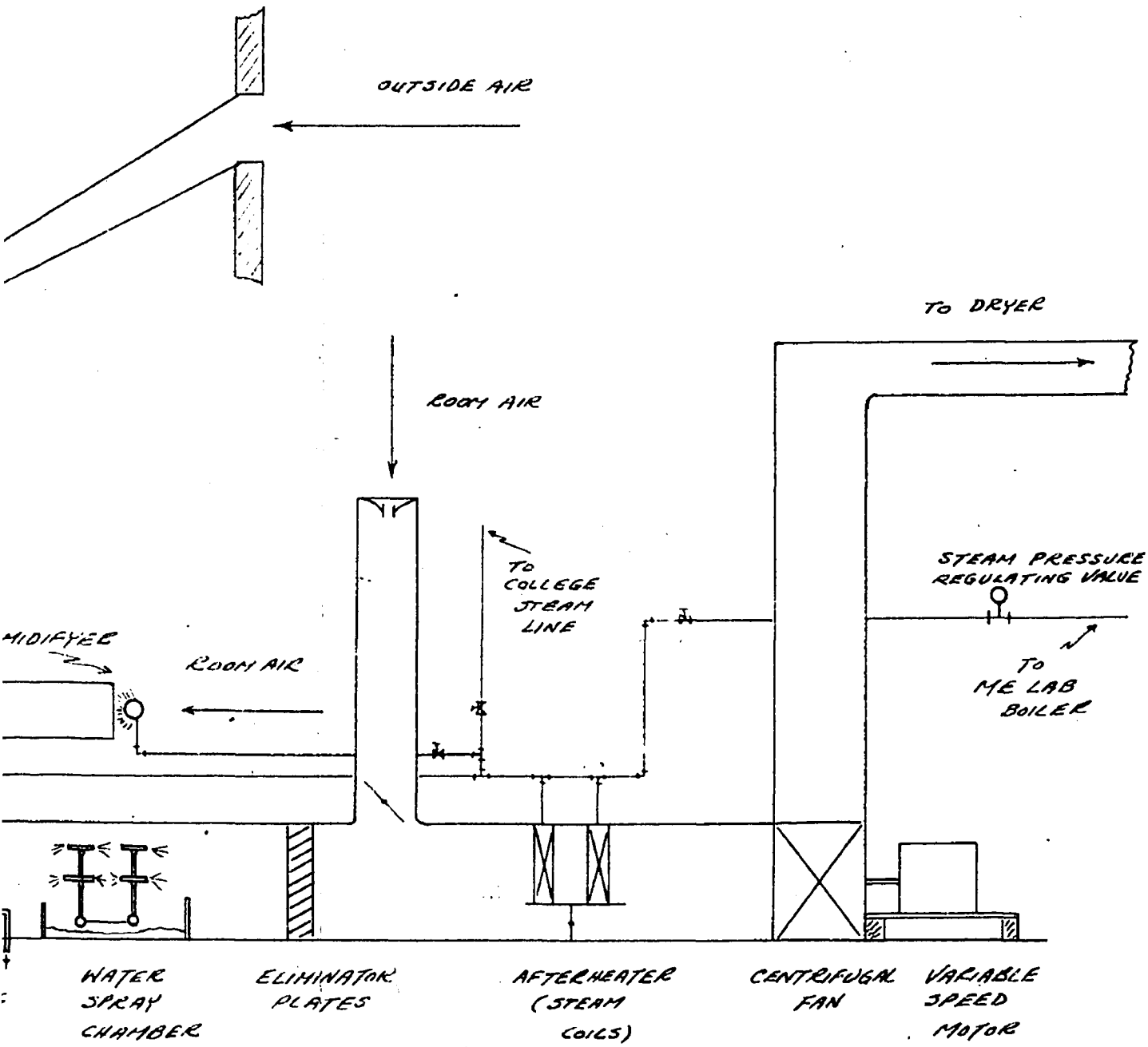
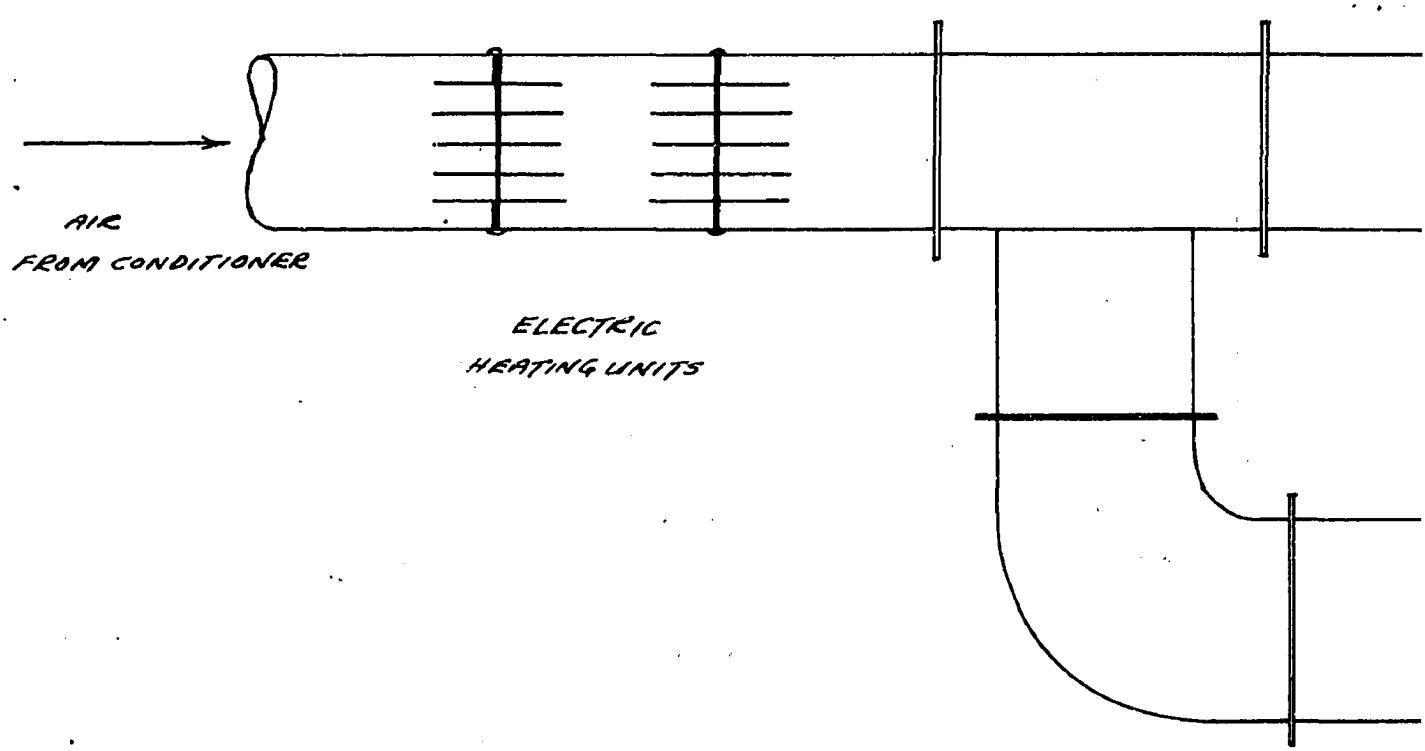


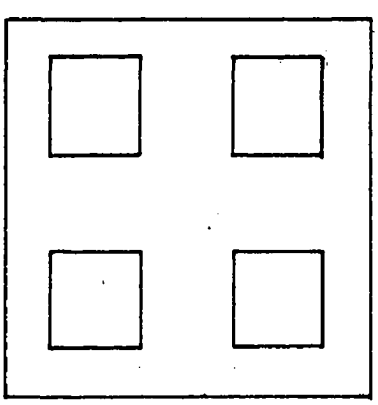
FIGURE 7. SCHEMATIC DIAGRAM OF AIR



SCALE - 3/16 IN. = 1 FT.

SCHEMATIC DIAGRAM OF AIR CONDITIONER





SECTION A-A

26 GAGE SHEET METAL
CLIP LOCK SEAM CONSTRUCTION
ALL SEAMS SOLDERED

SCALE 1/2 IN. = 1 FT

FIGURE 8

DRYING CABINET

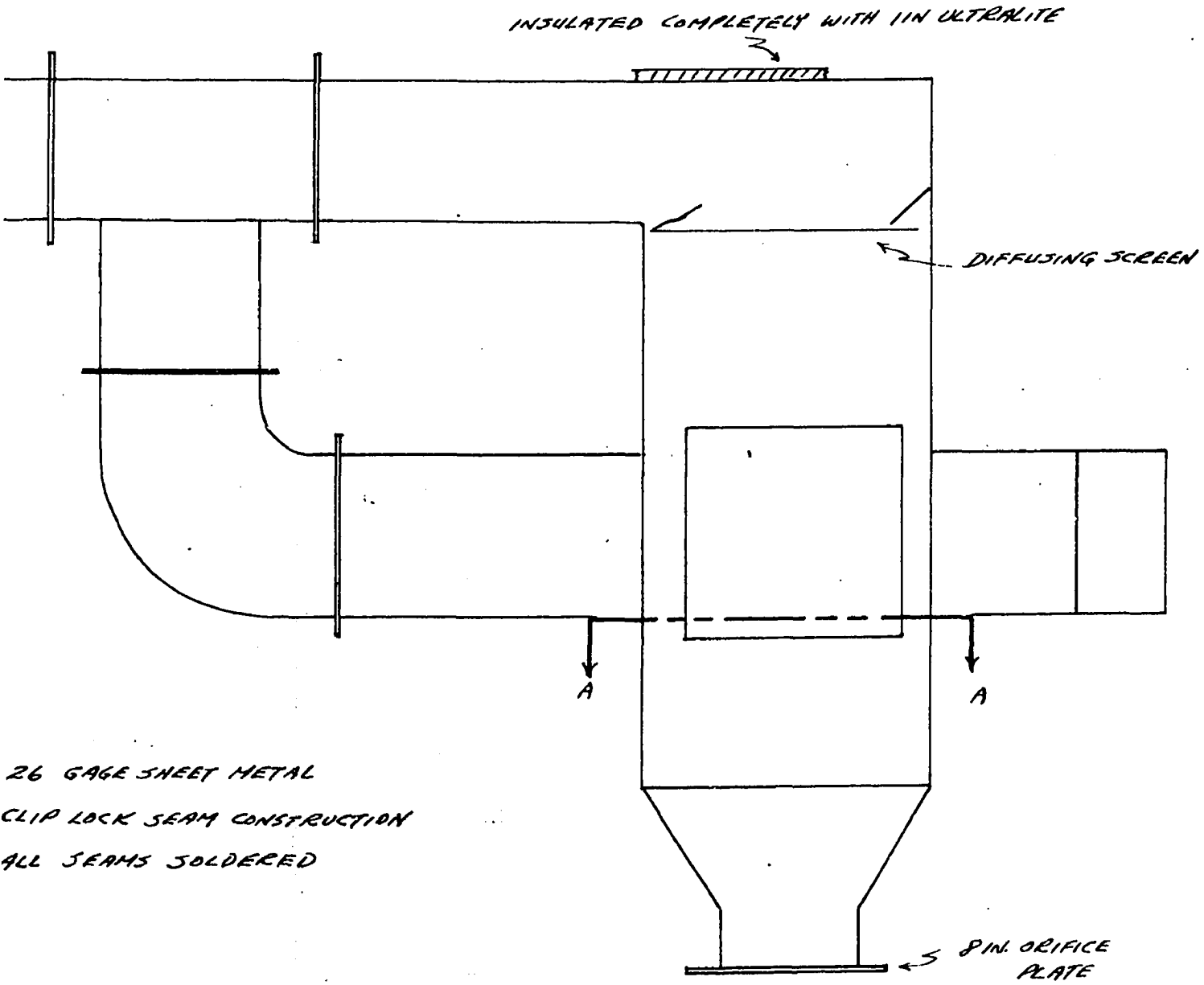


FIGURE 8

DRYING CABINET

ly actuated pressure regulating device, so steam flow may be held at any desired pressure. Maximum steam pressure from the boiler is about 120 psi.

Filters

Removable filters of the dry type are provided at the entrance to the apparatus. A bank of eight filters approximately two feet square is installed in a staggered arrangement.

Steam coils

Four steam heating coils are included; a bank of two coils is placed after the filters, and the other two are at the end of the conditioner ahead of the fan. The latter set of coils will be called the afterheater. All of the coils are Trane Company series 85 type E blast coils. Each row is 24 by 36 inches with 1/2 inch copper tubes. The tubes are finned with 1/16 inch aluminum fins, and have a cast iron header with a galvanized casing.

Steam flow to each coil is regulated with a Minneapolis-Honeywell type M904 Modutrol motor-operated steam valve. A Minneapolis-Honeywell type T915 temperature controller is connected to the valve motors, with thermostatic elements placed in the air stream after each bank of coils. The thermostatic control on the heating coils has a range of 55 to 110°F, and the range of the thermostat on the afterheater is 70 to 140°F.

Chilled water coil

This coil is a Trane Company type DX, six-row copper coil. It is a 24 by 36 inch coil, with 3/4 inch tubes. Make-up water is chilled in a shell and tube heat exchanger connected to the refrigeration machine.

Cooling coil

The cooling coil is also a 24 inch Trane Company type DX six-row finned tube 3/4 inch copper coil. This coil is connected to a ten-ton Frigidaire refrigeration unit. Freon-12 is employed as the refrigerant. The compressor is a V-type two cylinder unit, driven by a 7½ hp electric motor. A shell and tube condenser is included, using water as the cooling medium. The compressor is set to run at a constant speed of 1740 rpm, while the evaporator is connected to a thermostatically controlled expansion valve. This expansion valve is a Frigidaire model TEV set to close at a temperature of 35°F.

Air washer

A Trane Company type HDW air washer is installed with 16 nozzles and a SSU pump. Water may be either recirculated or heated in the chilled water system heat exchanger to a desired temperature.

Fan

The fan is a centrifugal type driven by a Century induction

polyphase motor. The motor is 3 phase, 60 cycle, 220 volts equipped with a starting box and 4 speed controller. Horsepower ratings of the fan are 3, 1.3, 0.75 and 0.33 at 1750, 1150, 870 and 570 rpm.

Drying Unit

Electric heaters

An electrical heating unit is located in the air supply duct to the drying cabinet. This unit was installed so that the air could be heated to a temperature above that obtainable with the steam coils. Also, since the thermostat on the steam afterheater has a maximum temperature limit of 140°F, the electric heaters may be used for fine temperature control at temperatures above 140°F.

Ten wire resistance heating grids are placed in the air supply duct. The grids are connected in parallel, with each grid wired to a knife switch. With this arrangement any number of grids may be put on or taken off of the line. The grids are connected to a DC line, with current furnished by a 40 hp Fairbanks-Morse motor generator set. The voltage output of the generator may be varied with a reostat from 40 to 125 volts.

Control of the output of heat from the electrical grids is possible by regulating both the number of grids and the voltage.

Drying cabinet

The drying cabinet is approximately 9 feet high, and 44 inches square. Two air inlets and outlets are incorporated in the design so that air may be blown either over or through the material to be dried.

The cabinet has a capacity of four one-foot square pans. Four samples of materials may be dried at a time. The pans are made of 24 gauge sheet metal with a copper hardware cloth bottom.

Instrumentation

Temperatures

Wet and dry bulb temperatures of the air supplied to the drying unit were taken in the supply duct to the cabinet at a point midway between the electric heaters and the fan. For the dry bulb temperature, a mercury-in-glass thermometer shielded with aluminum foil was placed in the air stream near the top of the duct where (according to a velocity profile) the velocity was the highest. A mercury-in-glass thermometer with the bulb covered with a wetted wick was used for the wet bulb determination, and inserted in the air stream close to the dry bulb. Both thermometers used were initially calibrated against a calorimeter thermometer certified by the National Bureau of Standards. These temperatures were taken to determine the dew point of the air supplied.

Wet bulb temperature of the air leaving the unit was determined with a Taylor Tycos motor driven wet bulb recording unit. Air temperatures in the drying unit were taken on both sides of the cabinet about one foot above the trays with a Bristol two-point recording unit. The temperature of the air leaving the unit was determined below the trays with a Bristol recording unit.

Air flow

Air flow was determined with an Alnor velometer at the drier exit. An 8 inch orifice was fitted to the exit duct to increase the exit air velocity, in order to keep the wet bulb recording unit from drawing room air into the drier. A traverse was run over the orifice, to determine the average exit velocity.

Air velocities were also measured with a pitot tube in the 20 inch supply duct to the drier at the higher velocity. These values obtained were within about 2 percent of the velocity obtained with the velometer. For the majority of the test work the air velocity in the duct was too small to get a reliable pitot tube reading.

TESTS AND PROCEDURE

Drying tests were made on both soybeans and shelled corn. The soybeans were Hawkeye variety planted June 14, 1950, and combined October 13, 1950. These soybeans were grown on the Agronomy farm of the Iowa State College. The corn was a mixture of several hybrid varieties planted during the first week of July, 1950, and picked by hand October 17, 1950. All of the corn was shelled by hand since it was high in moisture content when picked. The corn was grown on the Agricultural Engineering Department experimental farm of the Iowa State College.

Preparation of Samples

All of the soybeans and corn were first put through a grain divider and separated into two similar portions; then each of these portions was divided, and finally each of the resulting divisions was again redivided. In this manner, the original samples were divided into eight divisions. Each of the final portions theoretically should have contained the same number of each kernel size. The samples were then put into glass containers and the corks were sealed into place with wax. Then the samples were stored until used in the cold storage locker of the meat laboratory of the Iowa State College at a temperature of 35°F.

Moisture determinations were made before the containers were sealed with a Tag-Heppenstal moisture tester. Moisture content of the soybeans was approximately 18 percent; the corn was too wet to test (above 30 percent).

All of the corn was dried as taken from the cold storage, but moisture was added to the soybeans after they were stored on the day prior to drying. In each case, a calculation was made to determine the amount of water that had to be added to the soybeans to bring their moisture concentration above 0.35 (dry basis). Each sample to be dried was then put into a quart jar and the required amount of water added. The jars were shaken at about one hour intervals for the first eight hours, and the beans were kept in the jars for a minimum of 24 hours prior to the drying test.

Methods Used in Tests

Three series of tests were made on both the corn and soybeans. One series of runs was made with air supplied at a constant dew point of about 45°F, with the air velocity kept constant at approximately 38 fpm, and the air temperature was varied from 90 to 150°F. A second series was run with the air supply temperature maintained constant at 120°F, with the air velocity constant at about 38 fpm, and the dew point of the air supplied varied from 15 to 82°F. The third series was run at a constant air temperature of 120°F, a constant dew point of

about 45°F, and the air velocity varied from 23 to 53 fpm.

The methods used in conditioning the air for each run are illustrated in schematic psychrometric charts in Figures 9, 10, 11 and 12. For the 150°F runs, the afterheater thermostat was set at 140°F and the air supplied to the drier was heated with the electrical heaters. A constant temperature was maintained in this case by regulating the voltage to the heaters.

Four samples were dried during each test run. The samples were placed in the tray in a one kernel thickness covering the one square foot pan area. All tests were run with a through circulation air flow arrangement. Thus, the tests were made to simulate a full kernel exposure to air flow.

During the test run, the samples were removed from the drier at hourly intervals and weighed on a triple beam balance. Changes in moisture content were calculated from successive differences in the sample weights. Weighing of the four samples took from three to four minutes, so no single pan was out of the drier for more than a minute at each weighing.

After the air conditioner was shut down, the samples were left inside the drying cabinet for a period of 24 to 48 hours of air drying. After the air drying a sample was taken from each pan and ground in a mill, and a 20 - 30 gram sample was put into a vacuum oven and maintained at 90 - 100°C under a pressure of 0 - 20 millimeters of Hg for a period of 16 hours. The oven dried samples were then weighed and the final moisture content calculated. These final moisture content samples were

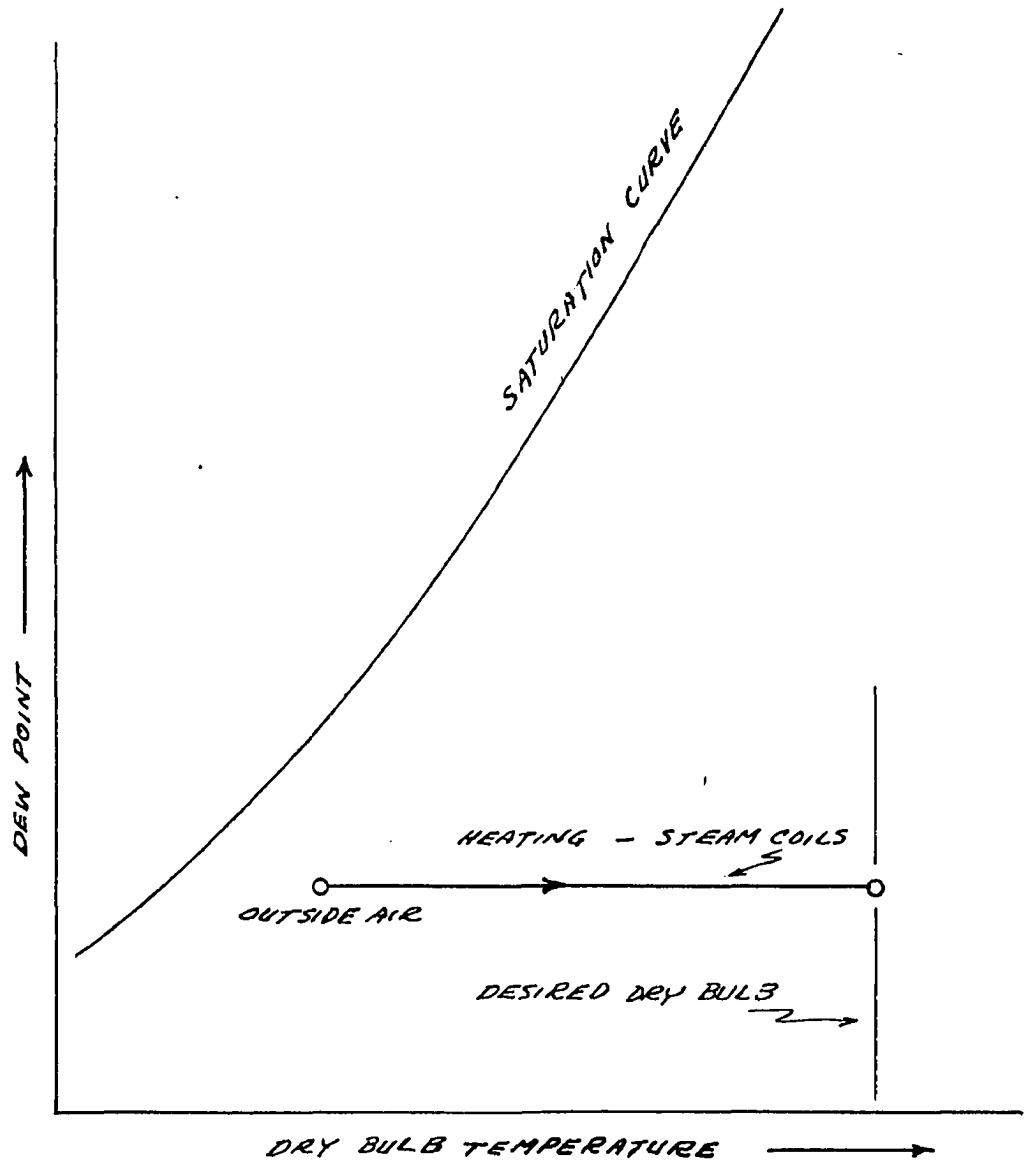


FIGURE 9.

SCHEMATIC PSYCHROMETRIC CHART - ILLUSTRATING METHOD OF AIR SUPPLY MAKE-UP

RUNS 1-5

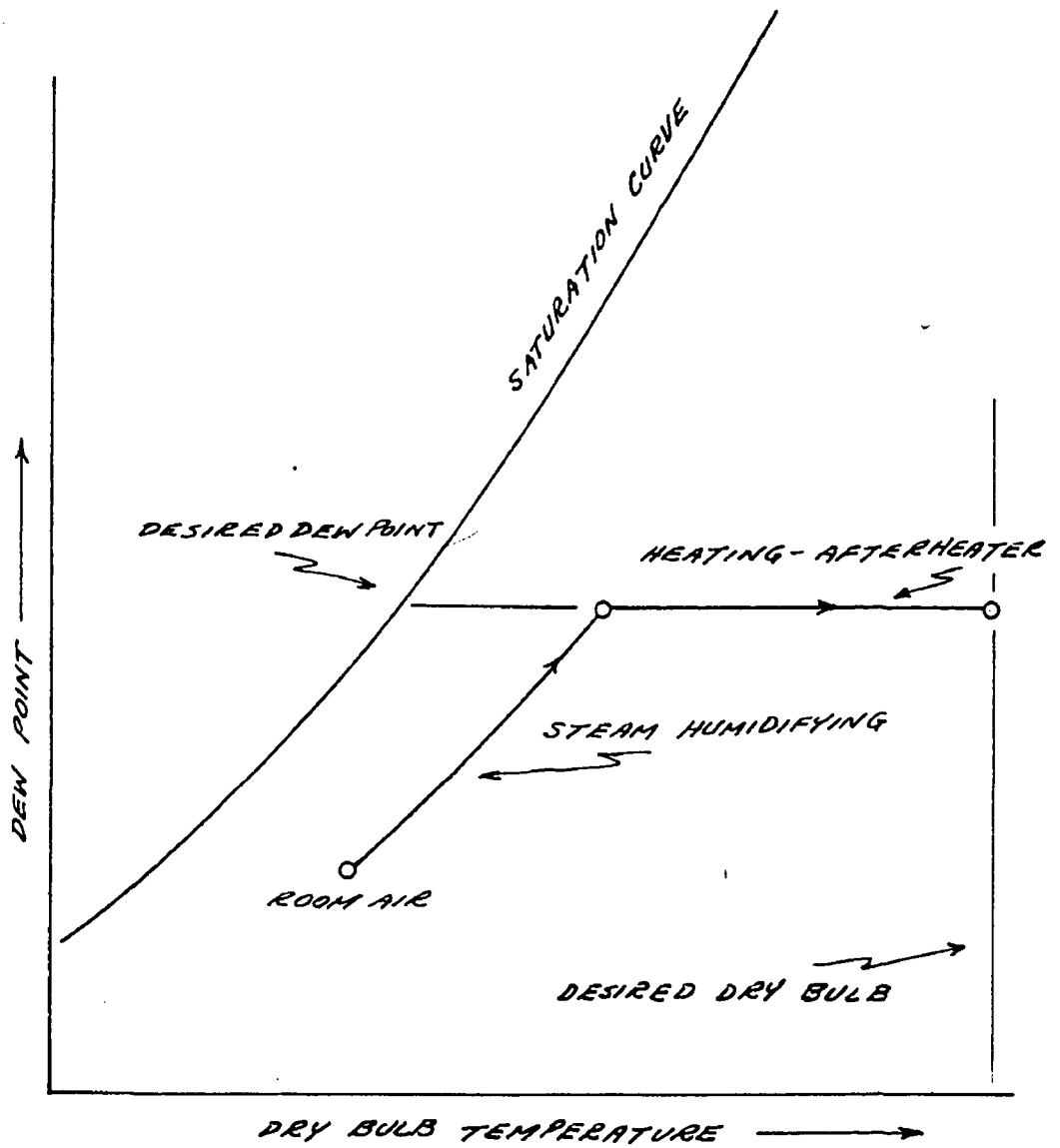


FIGURE 10.

SCHEMATIC PSYCHROMETRIC CHART - ILLUSTRATING METHOD OF AIR SUPPLY MAKE-UP RUNS 5-15, 17-19, 20-22

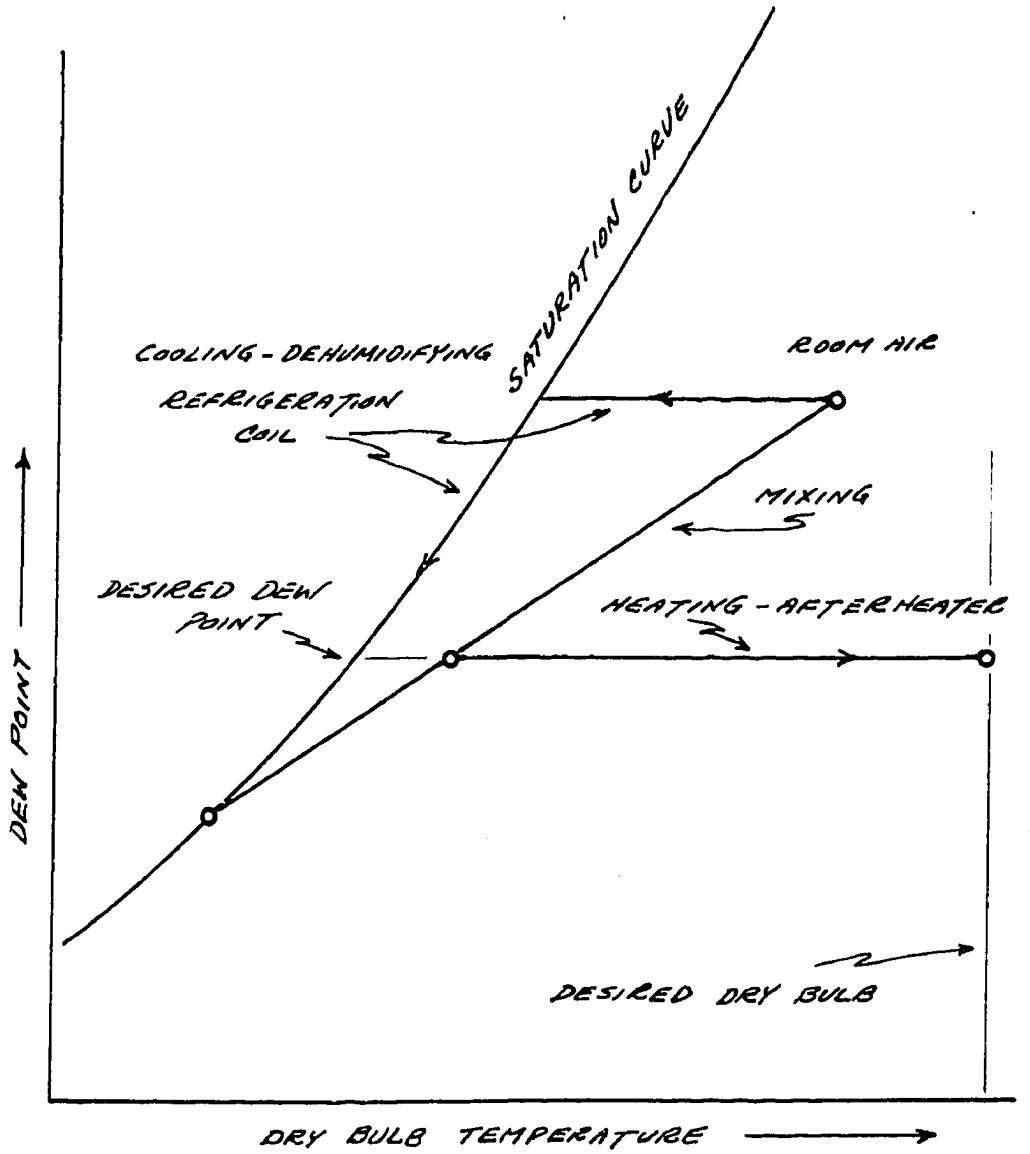


FIGURE 11.

SCHEMATIC PSYCHROMETRIC CHART - ILLUSTRATING METHOD OF AIR SUPPLY MAKE-UP

RUN 19

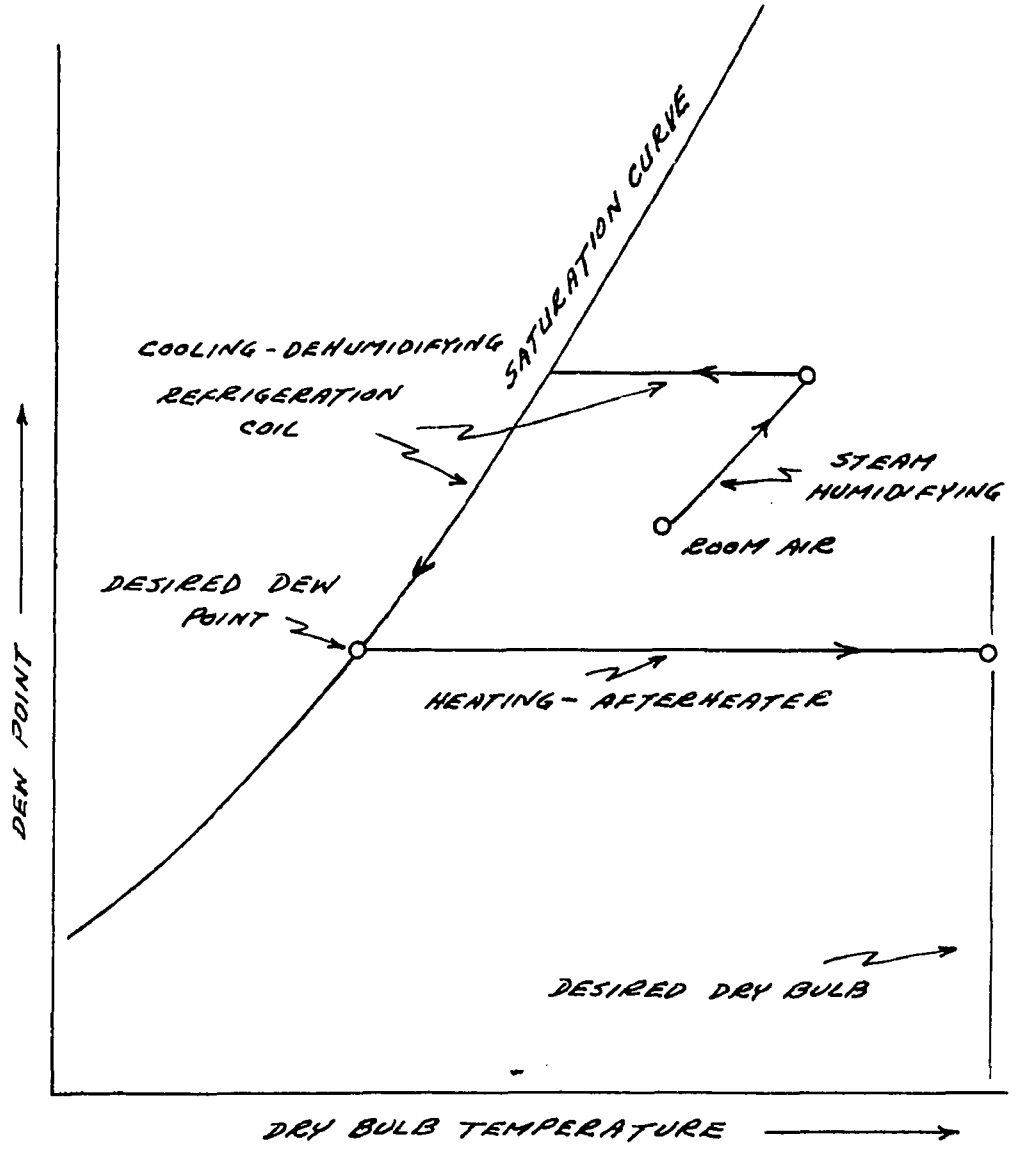


FIGURE 12.

SCHEMATIC PSYCHROMETRIC CHART - ILLUSTRATING METHOD OF AIR SUPPLY MAKE-UP

RUNS 15, 16

all weighed with an analytical balance. After several tests it became apparent that after air drying the samples were all at the same moisture content, so only two samples were taken for oven drying. Preliminary oven drying tests showed that the samples were virtually bone dry after 4 hours at 95°C and 20 millimeters Hg pressure, with negligible weight loss up to 8 hours. The samples were oven dried for 16 hours simply because they were put in at five o'clock in the evening and removed the following morning.

Accuracy of Measurements

Air temperatures were controlled with a thermostat with a variation of ± one degree. The desired dew point was maintained by maintaining the required wet and dry bulb temperature of the air. To hold a given wet bulb temperature, either a manual operation of the steam humidifier valve or mixing damper was required. The variation of wet bulb temperature during a run was held to a maximum of ± one half degree. Accuracy of the velometer is reported to be 3 percent by the Illinois Testing Company. As was previously pointed out, at the high velocity the velometer readings were within 2 percent of values obtained with a pitot tube. Least count of the triple beam balance used to weigh the samples was 0.1 gram. The analytical balance had a least count of 0.1 milligram.

Calculations

Since the velometer was calibrated to indicate the velocity of standard air (68°F, 29.92 in. Hg) the actual velocity was calculated with the equation:

$$V_o = (\text{velometer reading}) \sqrt{\frac{(460 + T)(29.92)}{(528)(\text{barometer})}} \qquad (34)$$

which relates the density of standard air to that of the actual air. However, this is the velocity at the 8 inch orifice (0.353 sq ft), so the air flow was calculated as:

$$Q = AV_o \quad (\text{cfm}) \qquad (35)$$

The total air flow was then divided by four to determine the flow of air through each drying tray. The partial pressure of the water in the air was calculated from the equations:

$$\frac{P_w}{P_a} = \frac{n_w}{n_a}$$

$$W = 0.622 \frac{n_w}{n_a}$$

which were developed in the section on psychrometric relations. Combining the equations:

$$P_w = \frac{WP}{0.622 + W} \qquad (36)$$

Specific humidity (W) was calculated by use of equation (13)

$$W_2 = W_1 - Z\left(\frac{P_2 - P_1}{P_2 - P_s}\right)$$

where values of Z were taken from Figure 4. The dew point of the air was taken from the Goff (9) low temperature moist air tables as the saturation temperature corresponding to the partial pressure of the water.

SUMMARY OF RESULTS

For each run moisture concentration (C) was plotted against time. Moisture concentrations were calculated on the dry basis. Figure 13 is included to illustrate a typical plot of these data. Each run had four drying curves. Then each of the curves was replotted with zero time at a given initial moisture concentration. The initial moisture content of the soybeans was taken as 0.35 and 0.30 was used for the corn. Thus, each of the curves was referred to the same initial moisture concentration, and the initial unsteady state warm-up period data were eliminated. Next, the moisture concentration value for each hour was taken from each of the four curves and averaged arithmetically - and finally an average curve of the four curves was drawn with these averaged data points.

For the soybeans, the adjusted data for the variable temperature series of runs are given in Figure 14, variable dew point series in Figure 15, and the variable air flow set in Figure 16. A similar set of results is given for the corn, with the variable temperature series in Figure 17, variable dew point in Figure 18, and the variable air flow runs in Figure 19.

Examination of the curves show that the rate of drying is definitely influenced by both the air temperature and dew point. It is apparent that the air velocity has no pronounced effect

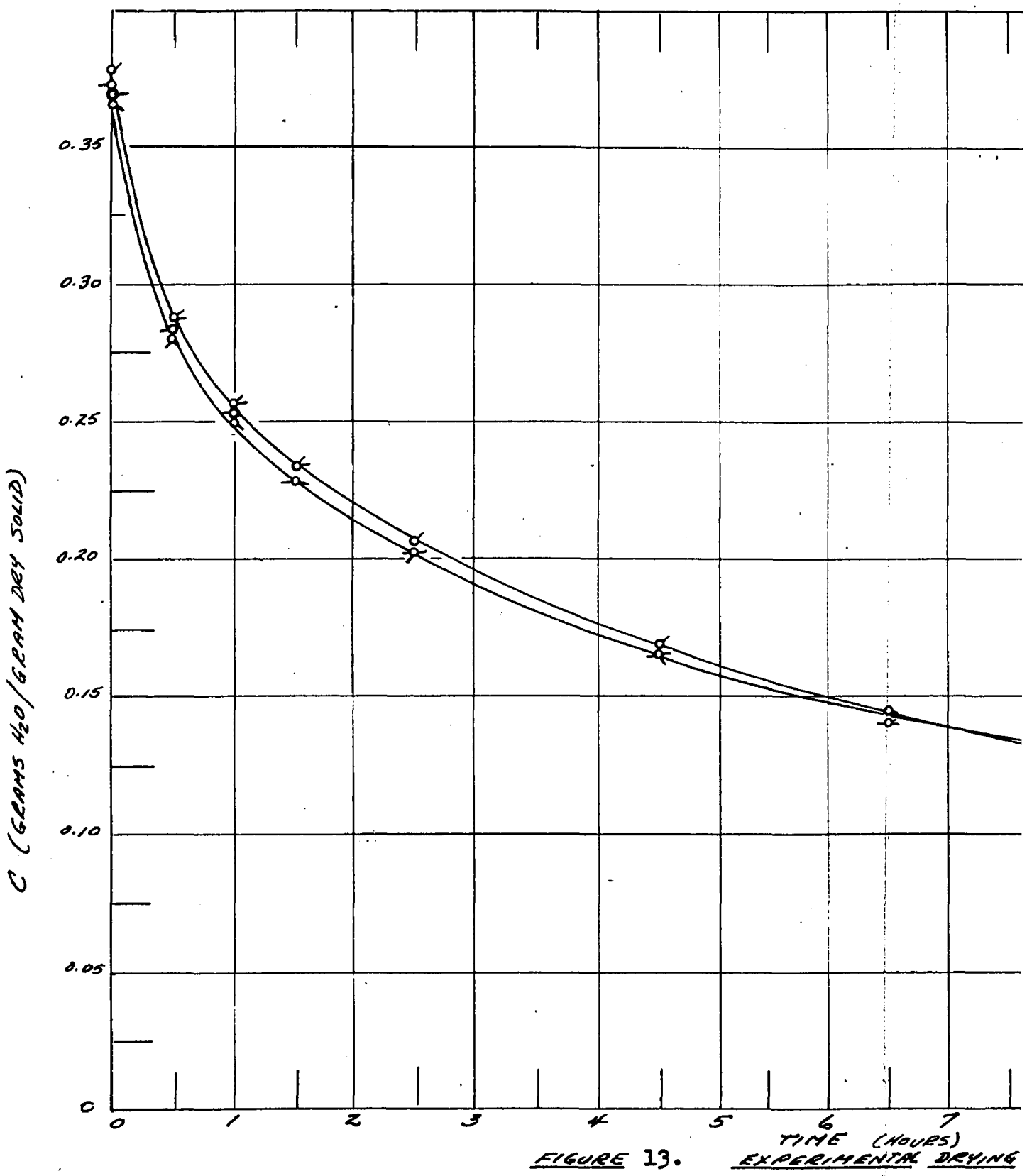
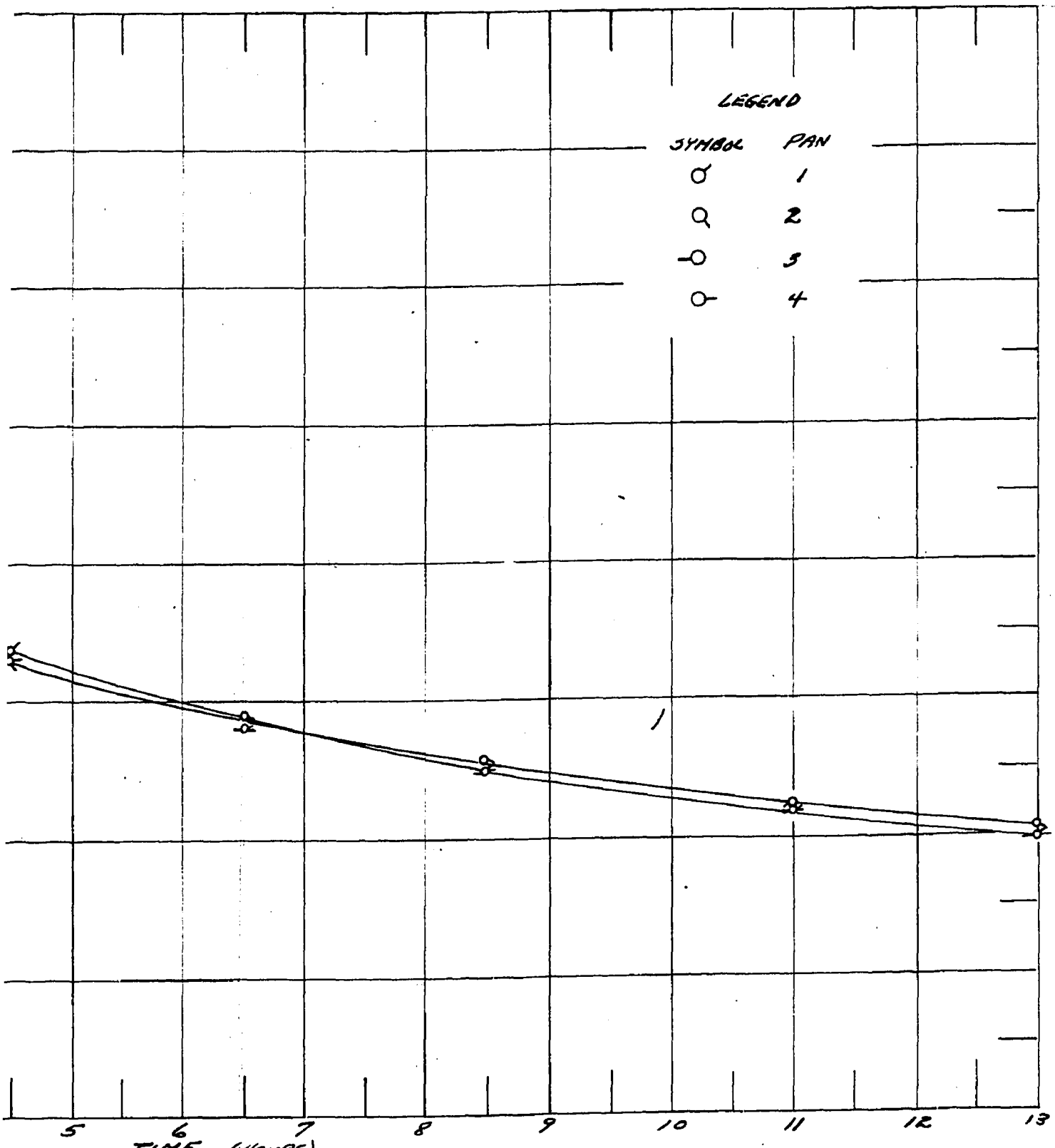


FIGURE 13. EXPERIMENTAL DRYING



.3. EXPERIMENTAL DRYING DATA - RUN No. 9

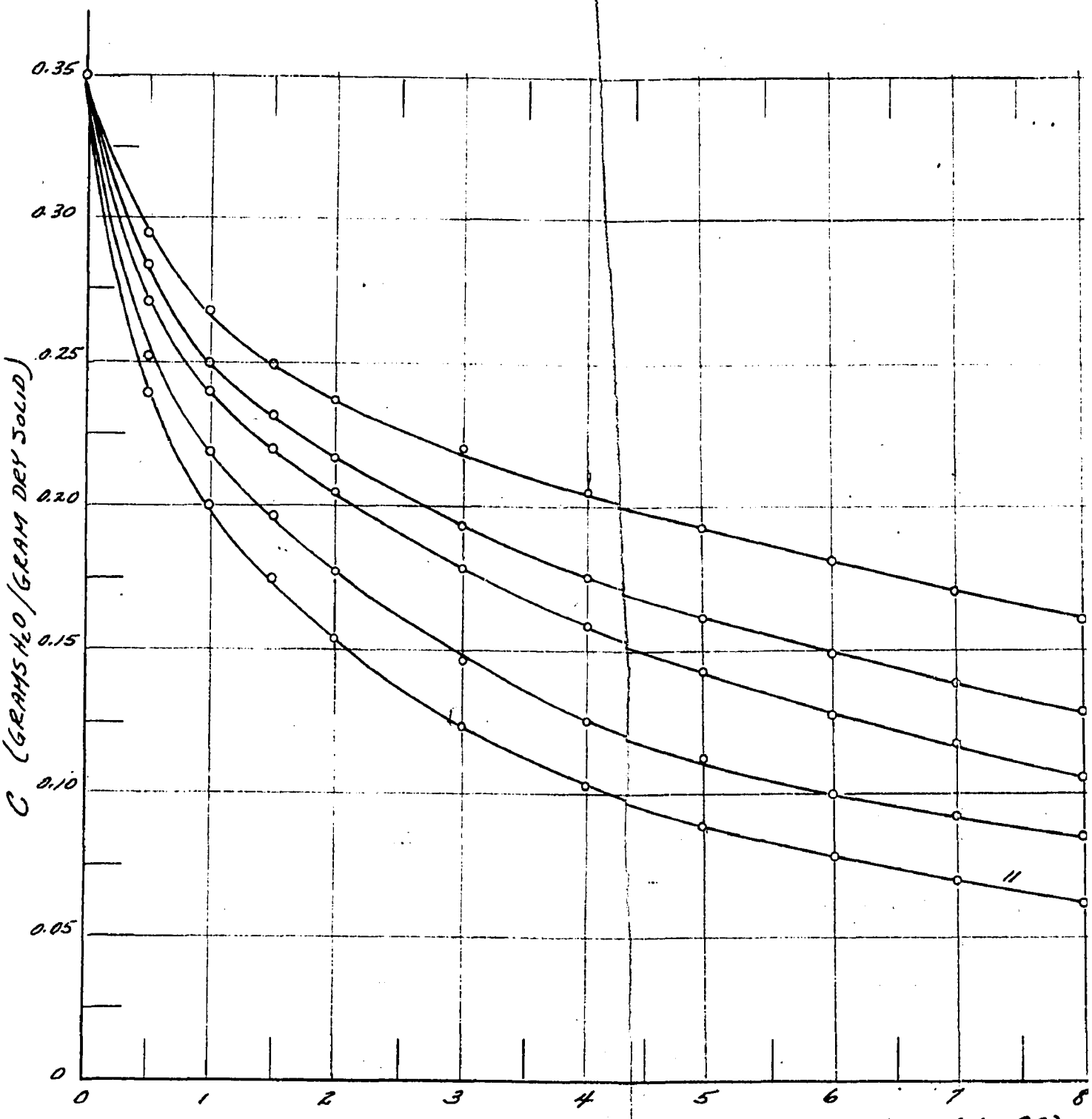
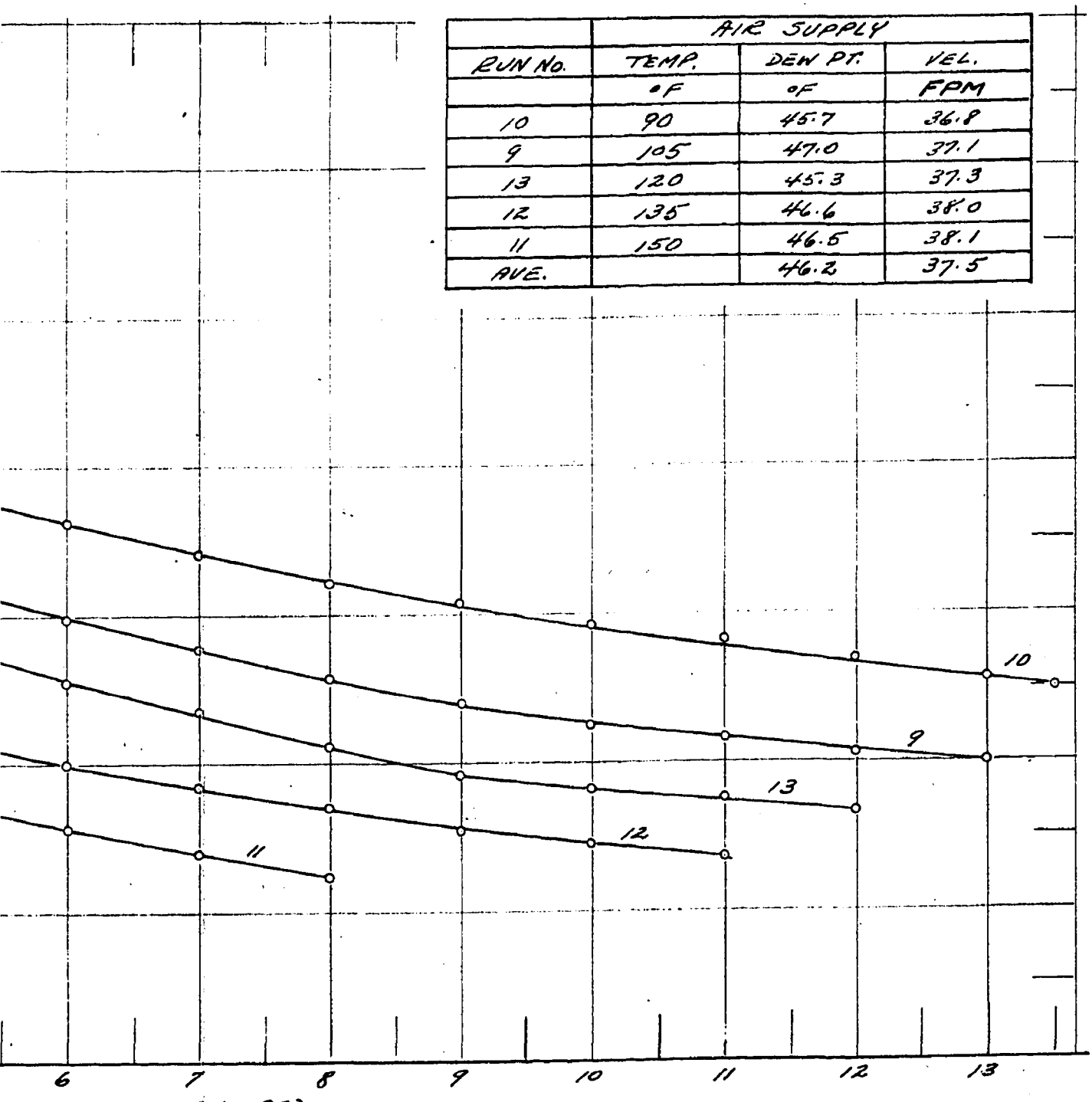


FIGURE 14. DRYING RATE - SOY

TEST CONDITIONS

RUN NO.	AIR SUPPLY		
	TEMP.	DEW PT.	VEL.
	°F	°F	FPM
10	90	45.7	36.8
9	105	47.0	37.1
13	120	45.3	37.3
12	135	46.6	38.0
11	150	46.5	38.1
AVE.		46.2	37.5



DRYING RATE - SOYBEANS

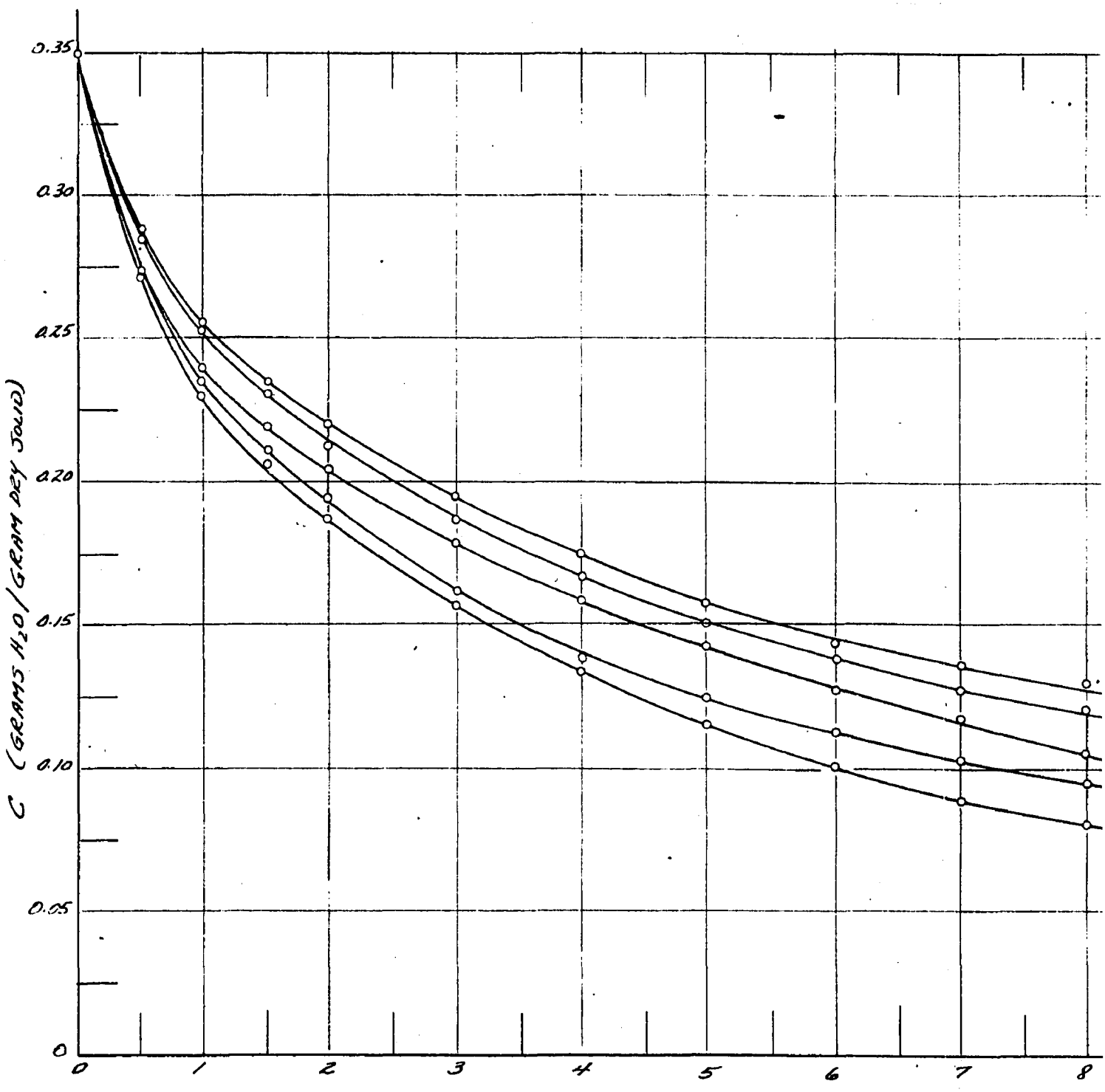
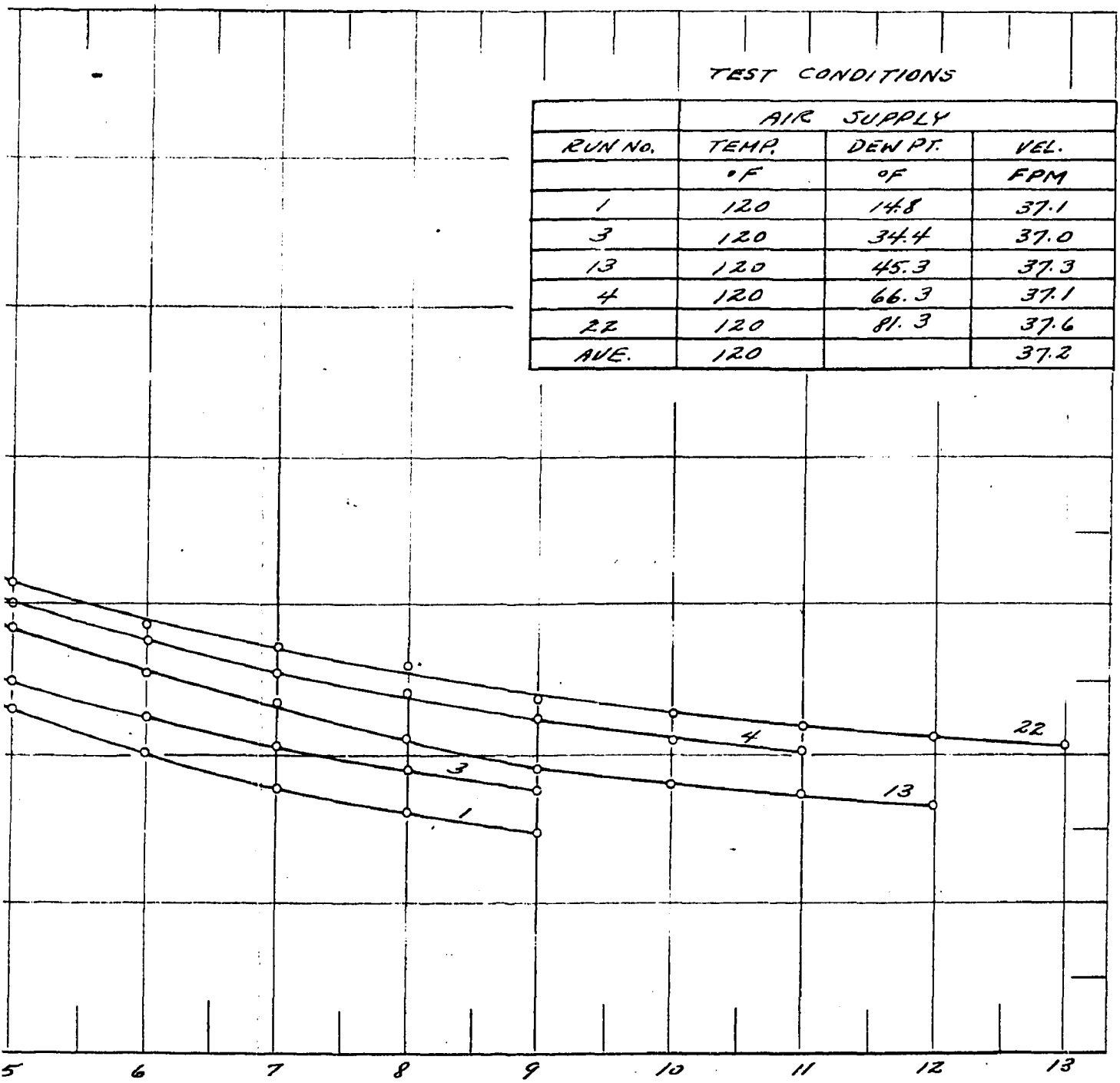


FIGURE 15. DRYING RATE - SO

TEST CONDITIONS

RUN No.	AIR SUPPLY TEMP. °F	DEW PT. °F	VEL. FPM
1	120	14.8	37.1
3	120	34.4	37.0
13	120	45.3	37.3
4	120	66.3	37.1
22	120	81.3	37.6
AVE.	120		37.2



E 15. DRYING RATE - SOYBEANS

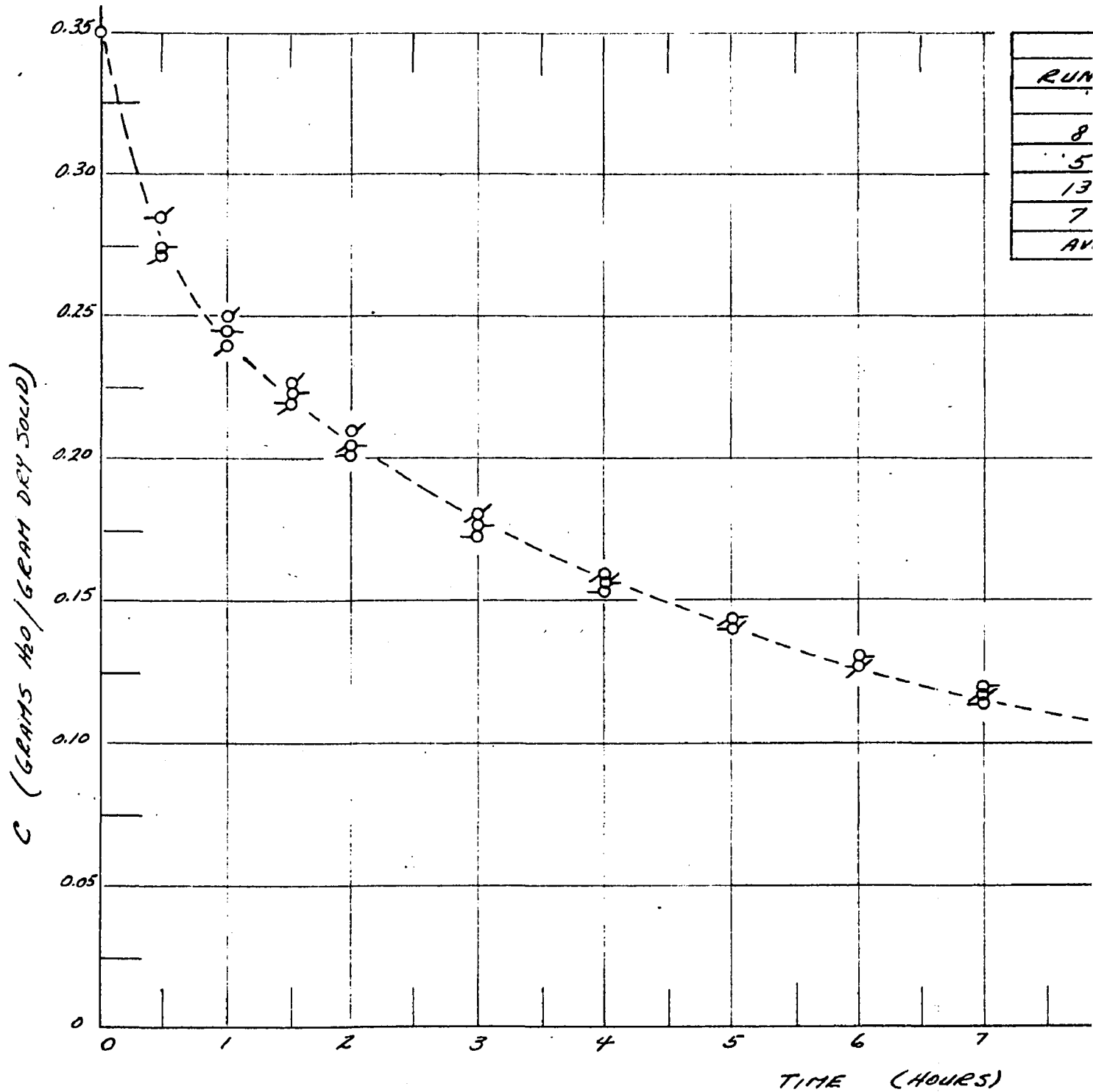
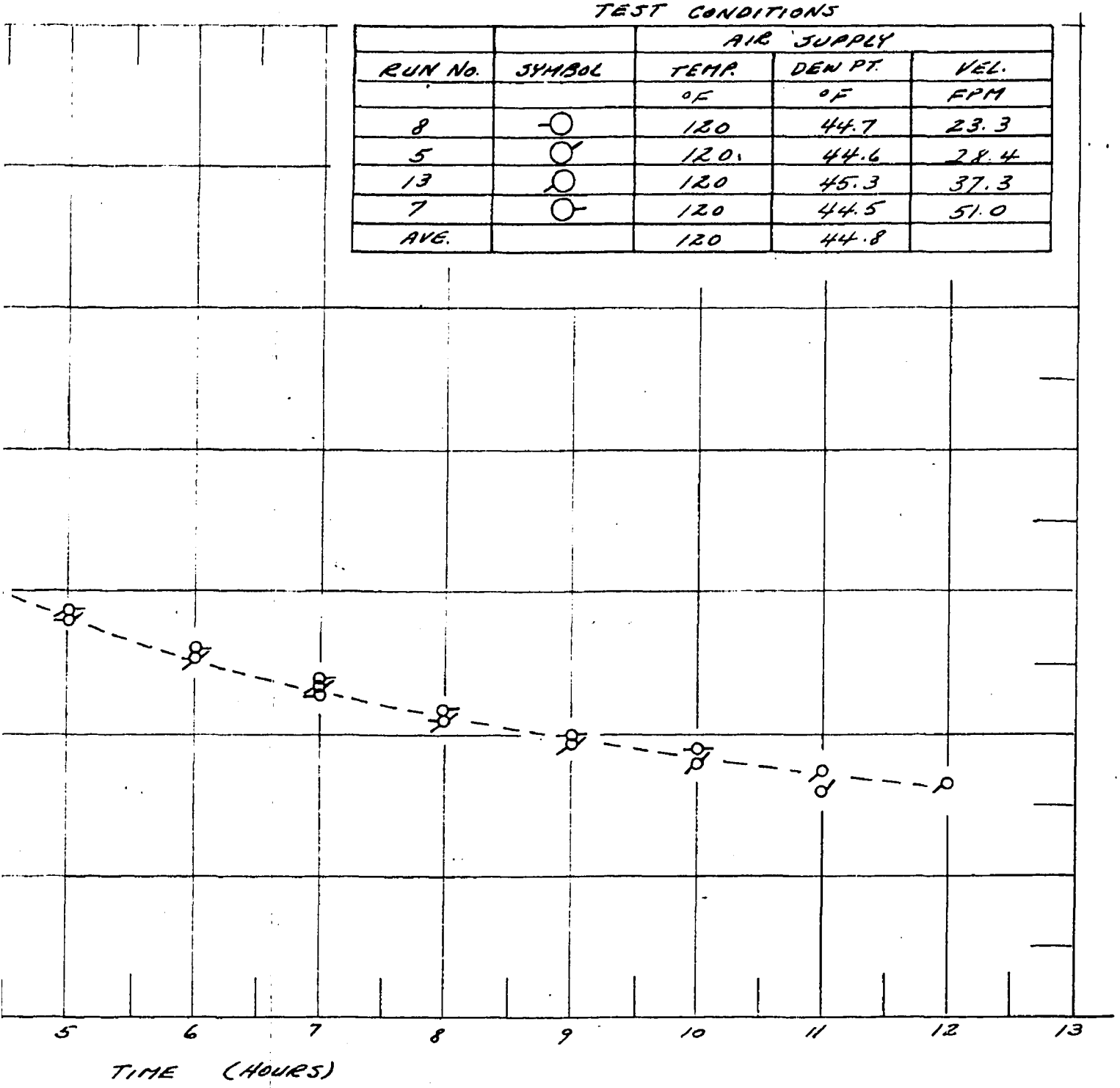


FIGURE 16. DRYING RATE - 30

TEST CONDITIONS

RUN No.	SYMBOL	AIR SUPPLY TEMP. °F	AIR SUPPLY DEW PT. °F	AIR SUPPLY VEL. FPM
8		120	44.7	23.3
5		120	44.6	28.4
13		120	45.3	37.3
7		120	44.5	51.0
AVE.		120	44.8	



IRE 16. DRYING RATE - SOYBEANS

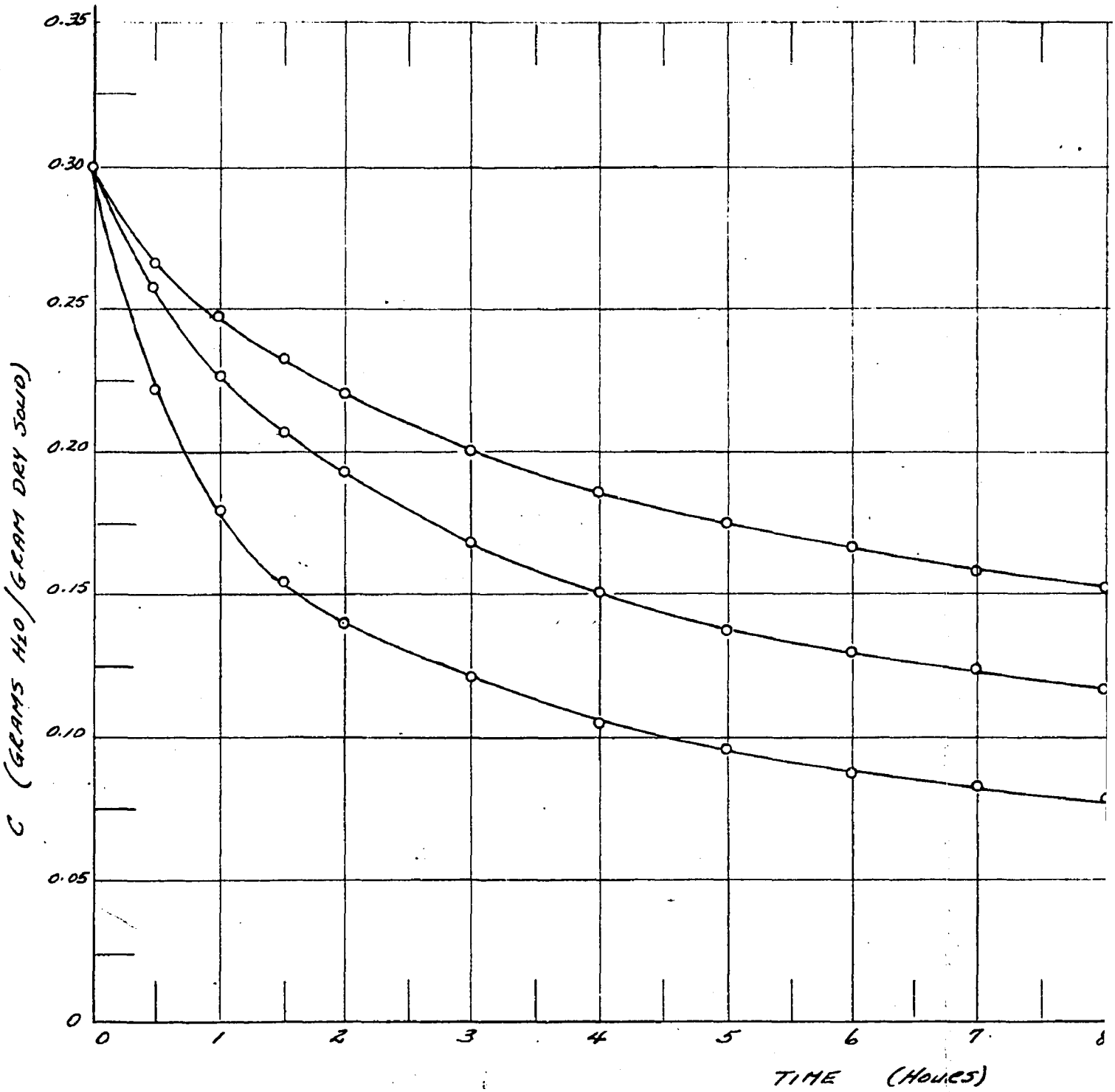
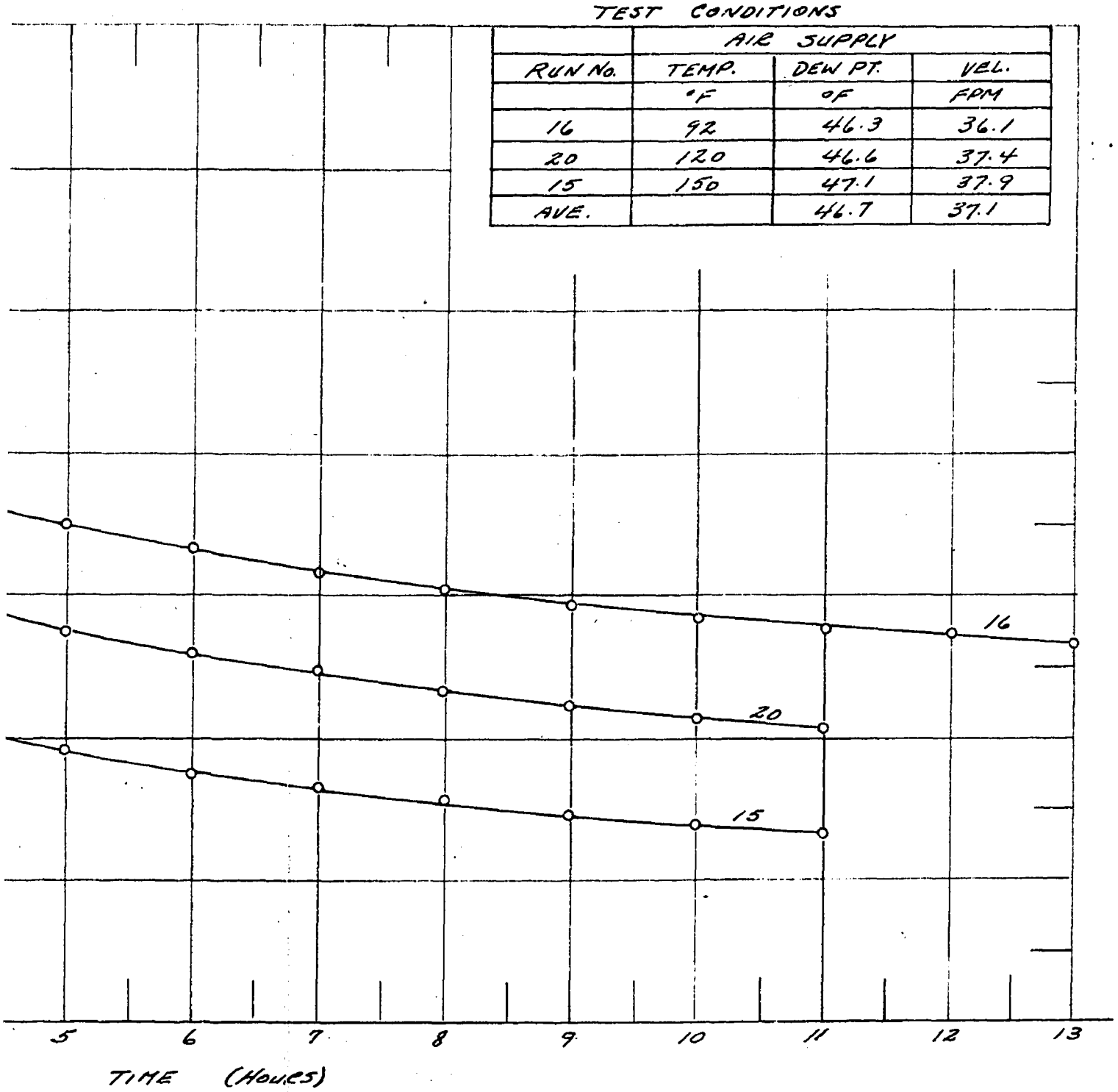


FIGURE 17. DRYING RATE - CO

TEST CONDITIONS

RUN No.	AIR SUPPLY		
	TEMP.	DEW PT.	VEL.
	°F	°F	FPM
16	92	46.3	36.1
20	120	46.6	37.4
15	150	47.1	37.9
AVE.		46.7	37.1



IRE 17. DRYING RATE - CORN

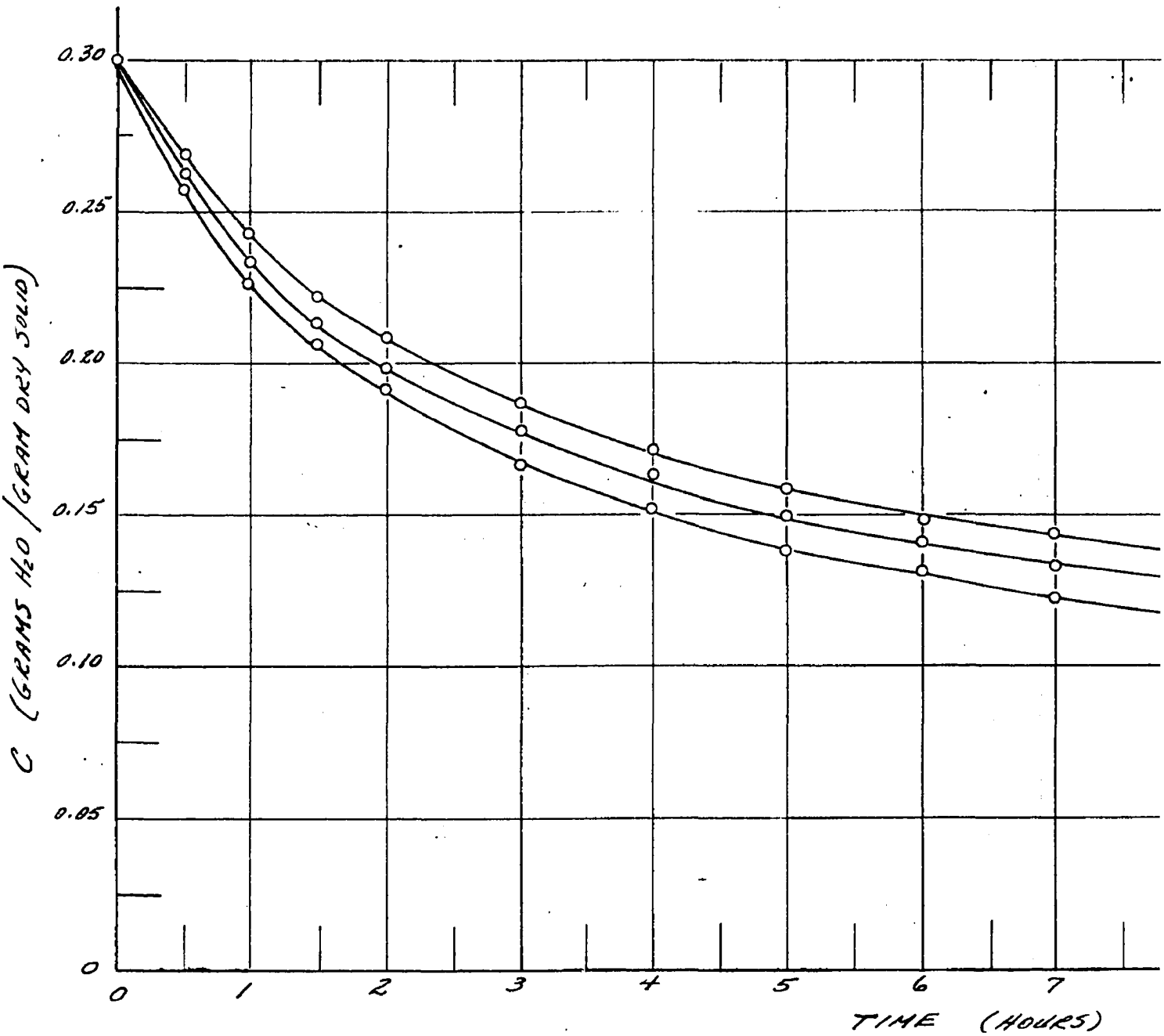
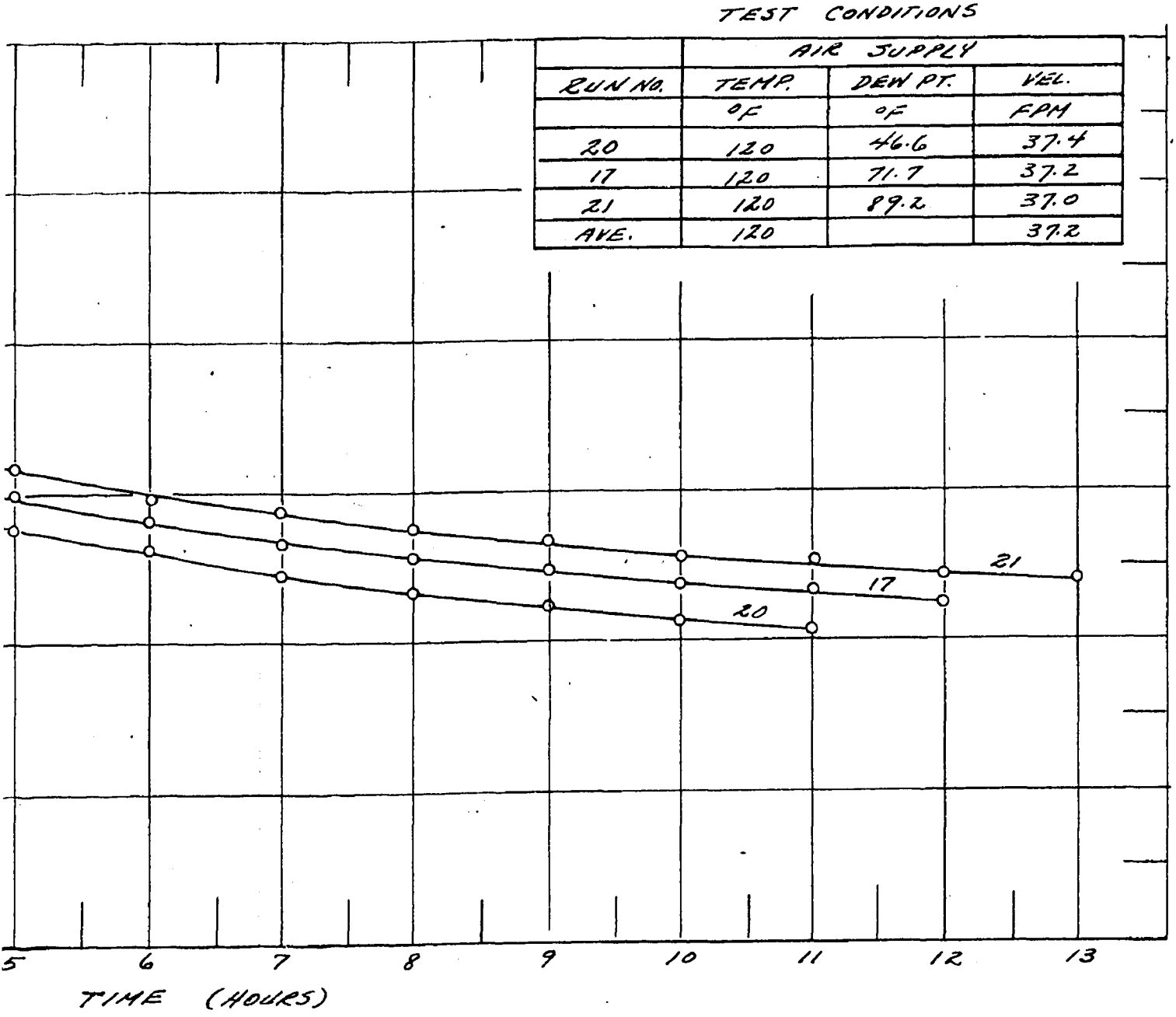


FIGURE 18. DRYING RATE -

TEST CONDITIONS

RUN NO.	AIR SUPPLY		
	TEMP.	DEW PT.	VEL.
	°F	°F	FPM
20	120	46.6	37.4
17	120	71.7	37.2
21	120	89.2	37.0
AVE.	120		37.2



RE 18. DRYING RATE - CORN

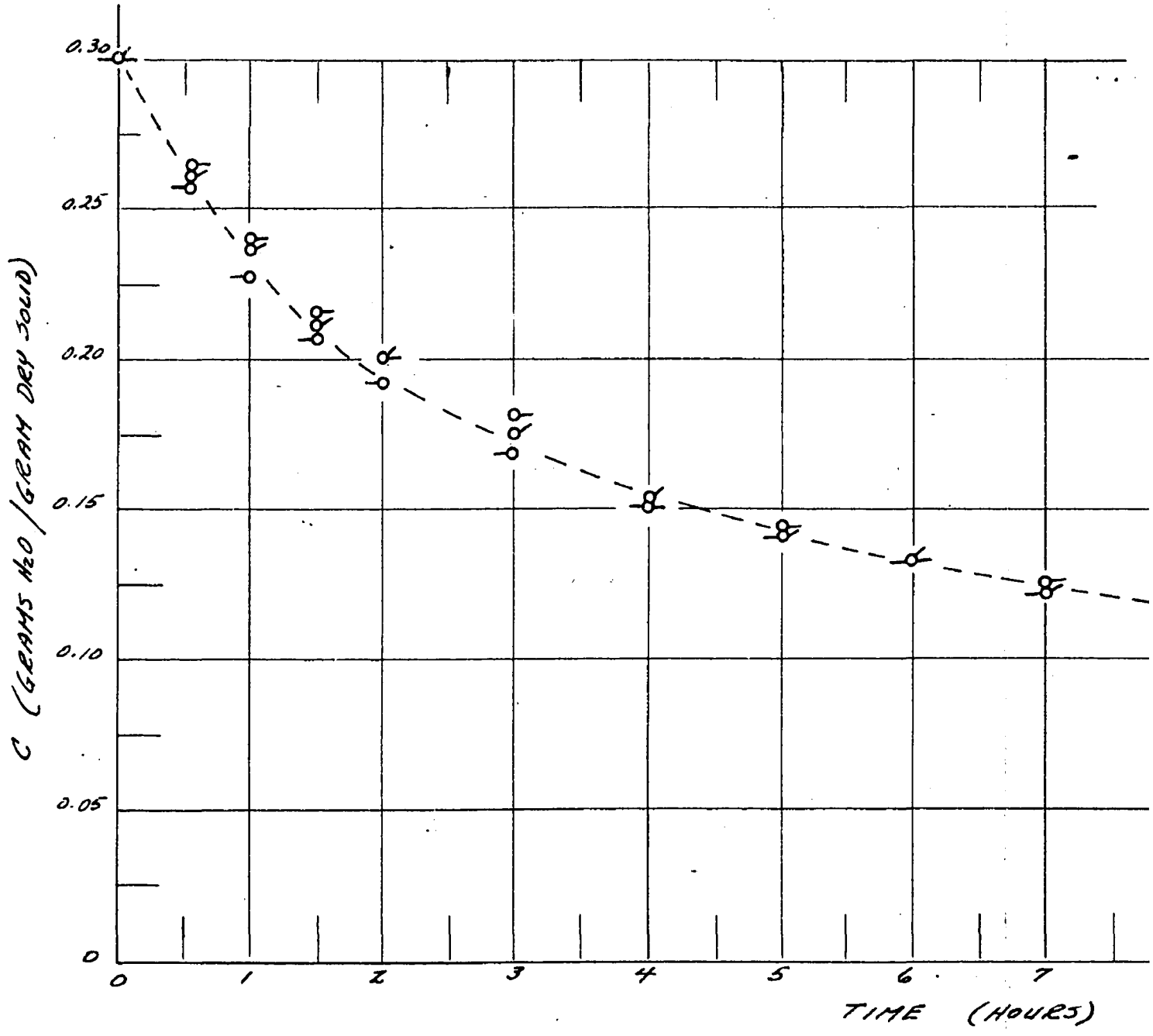
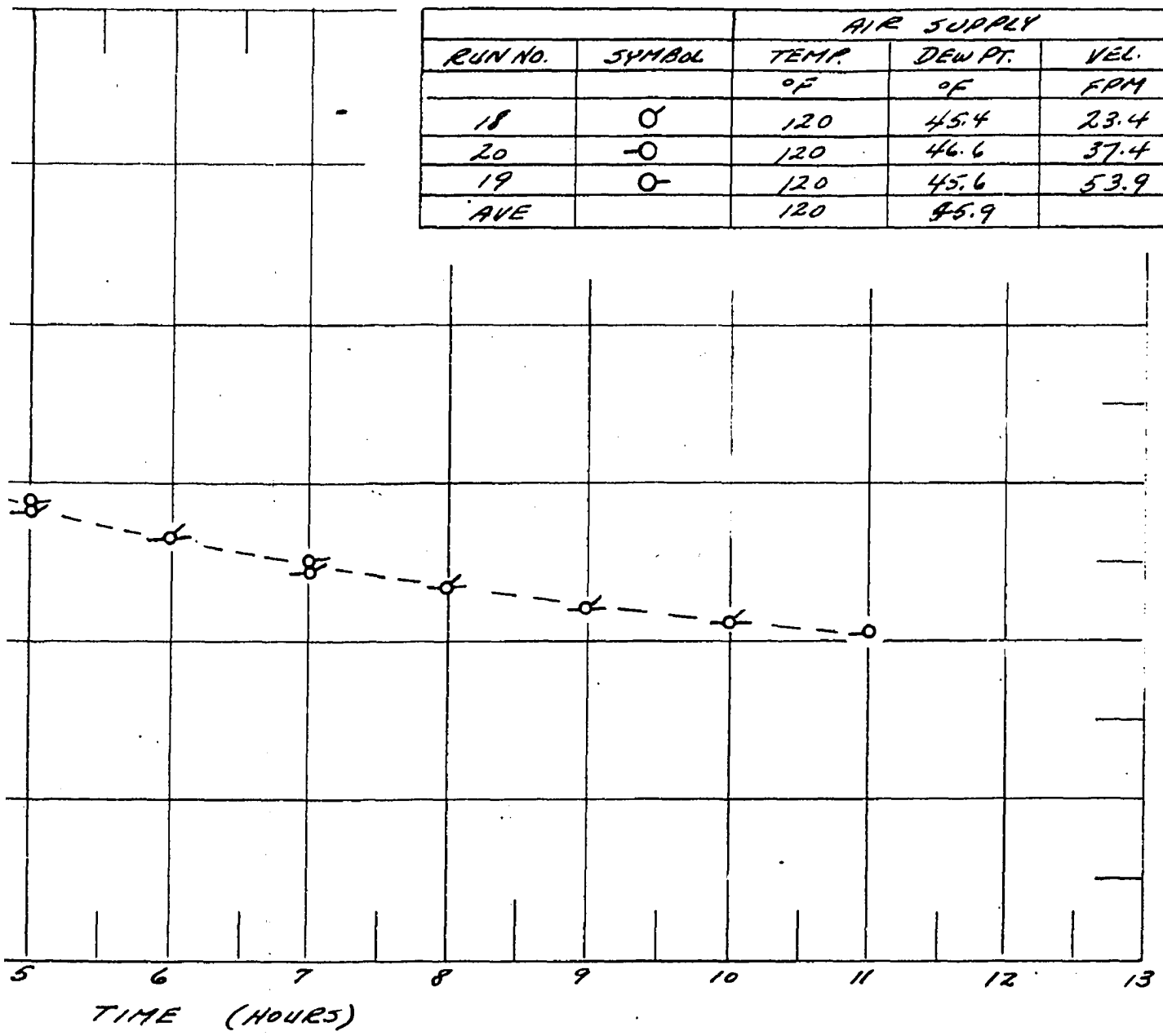


FIGURE 19. DRYING RATE -

TEST CONDITIONS

RUN NO.	SYMBOL	AIR SUPPLY TEMP. °F	AIR SUPPLY DEW PT. °F	AIR SUPPLY VEL. FPM
18	○	120	45.4	23.4
20	—○	120	46.6	37.4
19	○—	120	45.6	53.9
AVE		120	45.9	



IRE 19. DRYING RATE - CORN

on the rate of drying within the limits of the velocities used.

In addition, there is a marked similarity in the shape of both the soybean and corn curves, indicating that although the corn has a different drying rate the mechanism of drying in both cases may be the same. If the corn and soybean curves are compared, it may be noted that initially the corn dries faster than the soybeans. After several hours the curves intersect, resulting with further drying proceeding at a slower rate for the corn than the soybeans.

CORRELATION AND INTERPRETATION OF EXPERIMENTAL WORK

It has been shown that the air velocity has no effect on the drying characteristics of either the corn or soybeans, in the range studied. Hence, the dimensionless term:

$$\pi_3 = \frac{Vt}{R}$$

has no bearing on the problem and may be omitted.

Treatment of Soybean Data

The average moisture concentration at any given time is expressed in equation (32) as:

$$C_a = f\left[\frac{\pi^2 Dt}{R^2},\ \frac{Vt}{R},\ \frac{P_{sm}-P_w}{P}\right]$$

After eliminating the $\frac{Vt}{R}$ term, the equation is reduced to:

$$C_a = f\left[\frac{\pi^2 Dt}{R^2},\ \frac{P_{sm}-P_w}{P}\right]$$

Equation (31) also gives a relationship for the average moisture concentration at any given time, according to:

$$\frac{C_a}{C_o} = \frac{6}{n^2\pi^2} \sum_{1}^{\infty} (\exp)-\left(\frac{n\pi}{R}\right)^2 Dt$$

Experimental data obtained were values of moisture concentration

for various values of time and under different conditions of $\frac{P_{sm}-P_w}{P}$.

Values for $(\frac{C_a}{C_o})$ were calculated from the C-time curves obtained in the drying runs. Then, for these values of $(\frac{C_a}{C_o})$ the value of the dimensionless group $(\frac{\pi^2 Dt}{R^2})$ was calculated with equation (31). The value of $(\frac{P_{sm}-P_2}{P})$ was also calculated for each run. Figures 20 and 21 are a plot of $(\frac{\pi^2 Dt}{R^2})$ against time. Examination of these curves reveals that the initial portions of the curves are straight, and then curve off with increasing time. This indicates that $\frac{D}{R^2}$ is constant during the initial stages of drying, and then decreases as the moisture concentration decreases. Assuming that the radius remains constant, it may be said that the diffusivity is constant initially, and finally decreases with decreasing moisture concentrations. It can be seen that the straight line portions of the curves terminate at approximately the point of $C_a = 0.16$. Each of the curves has the point corresponding to $C_a = 0.16$ indicated. It may, therefore, be concluded that drying takes place with two falling rate periods. In the first period the diffusivity is constant, and after C_a has been reduced to 0.16 further drying is carried out with a diffusivity decreasing with moisture concentration.

Next, the value of D was calculated for each point plotted. The radius of the bean, R, was determined by taking the arithmetic mean of the diameters of 50 beans selected at random, and

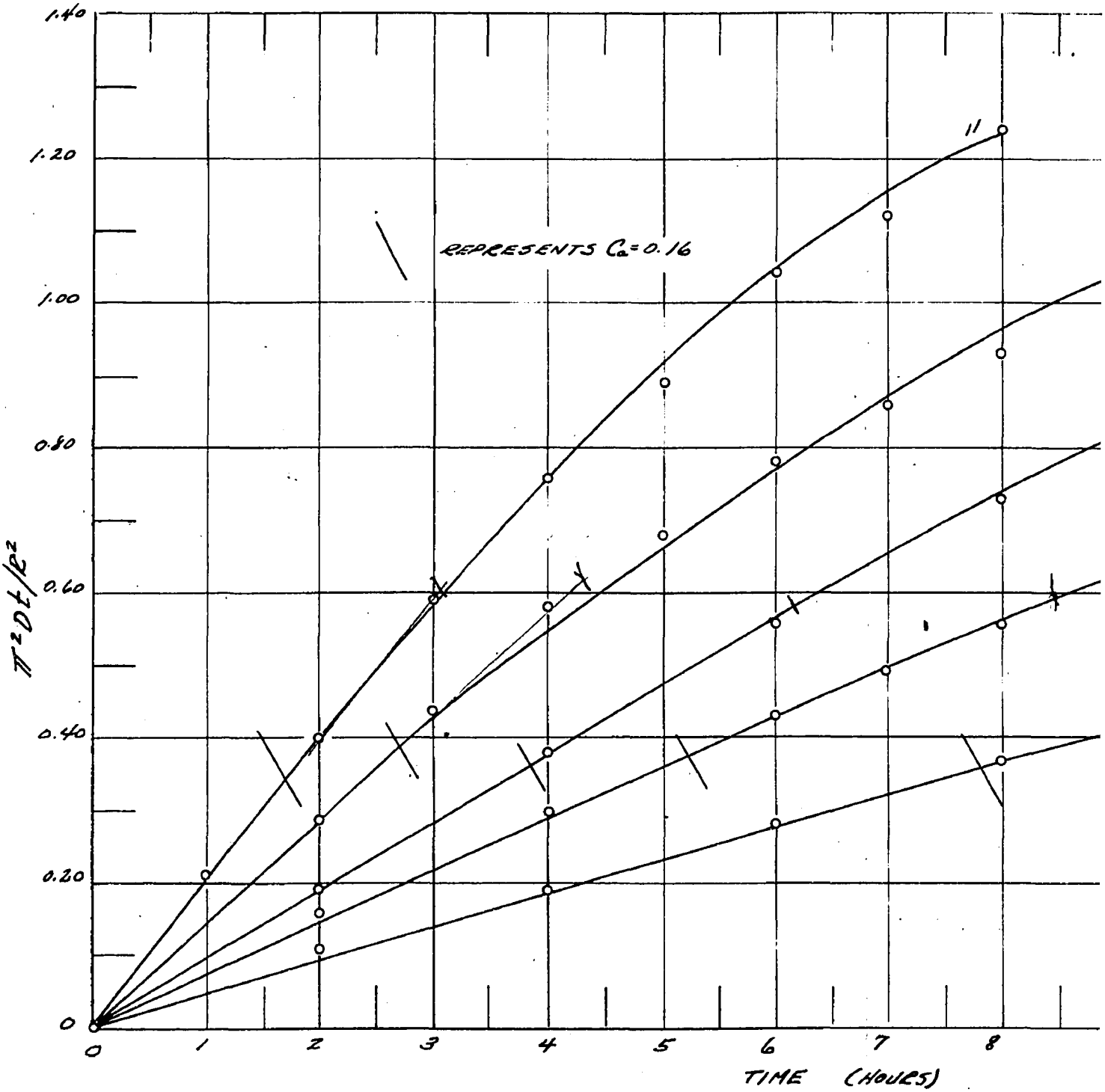
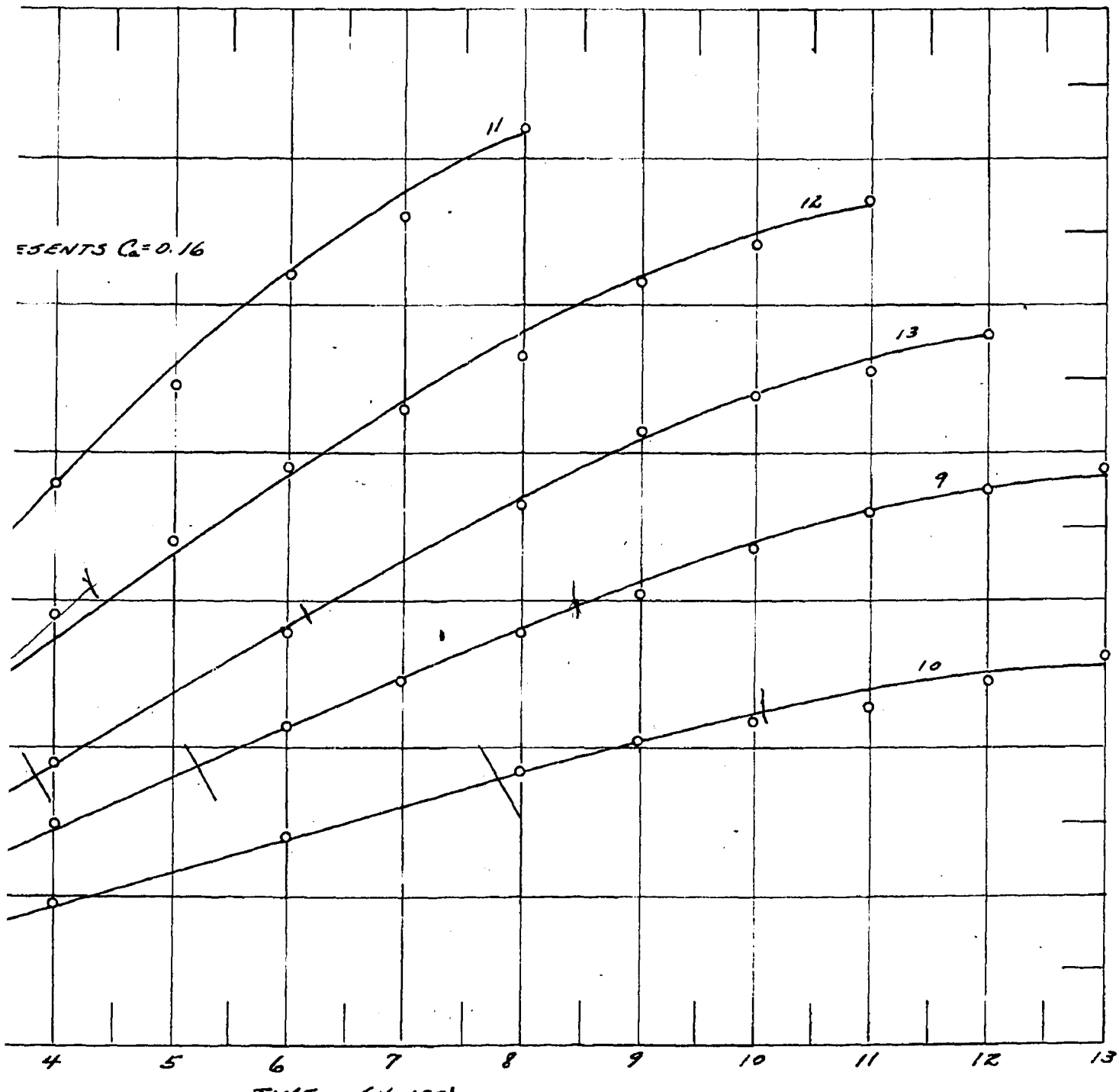


FIGURE 20 VARIATION OF $\pi^2 Dt/R^2$ WITH TIME - VARIABLE



ARIATION OF $\pi^2 Dt/R^2$ WITH TIME - VARIABLE TEMPERATURE SERIES (SOYBEANS)

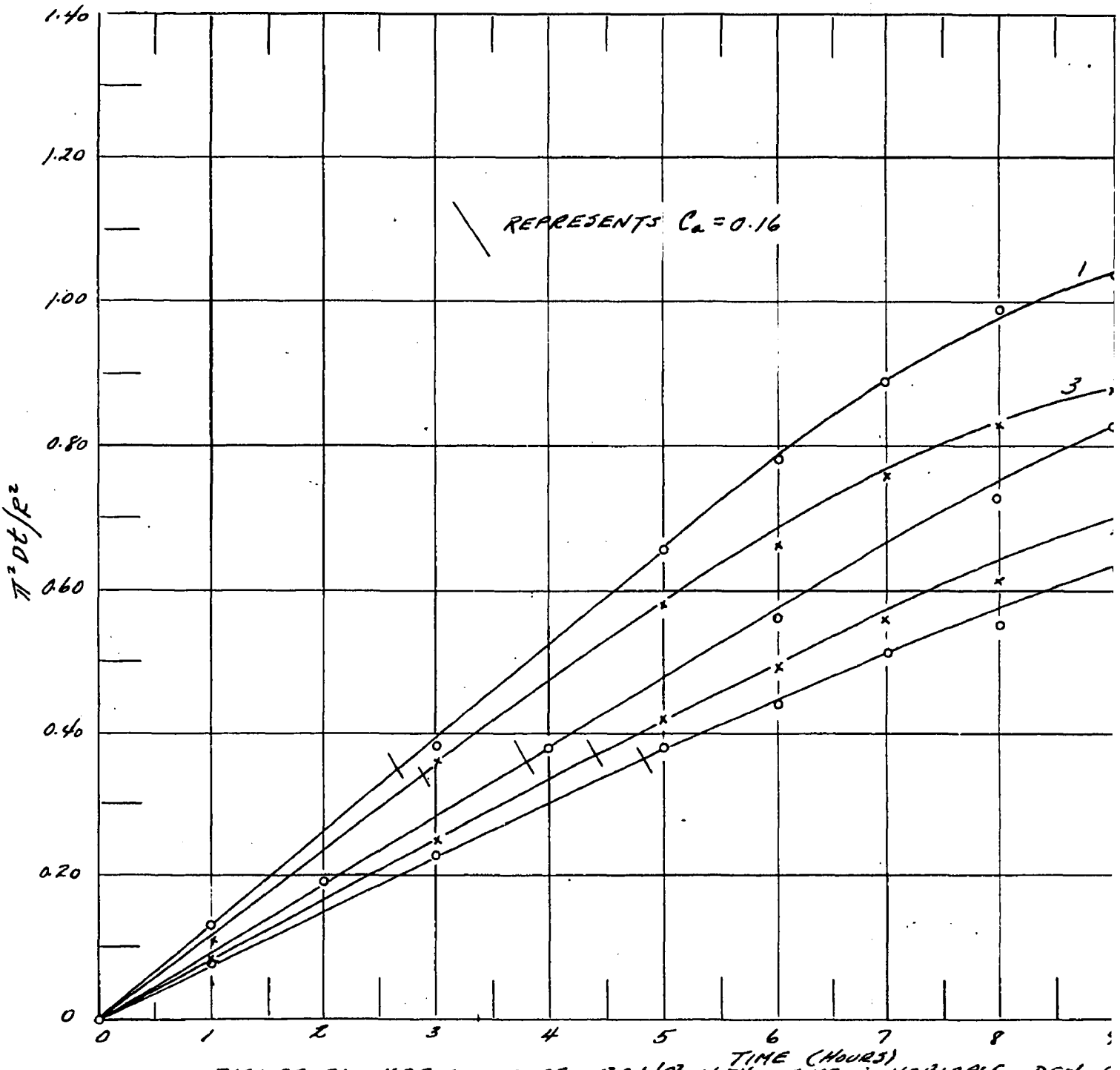
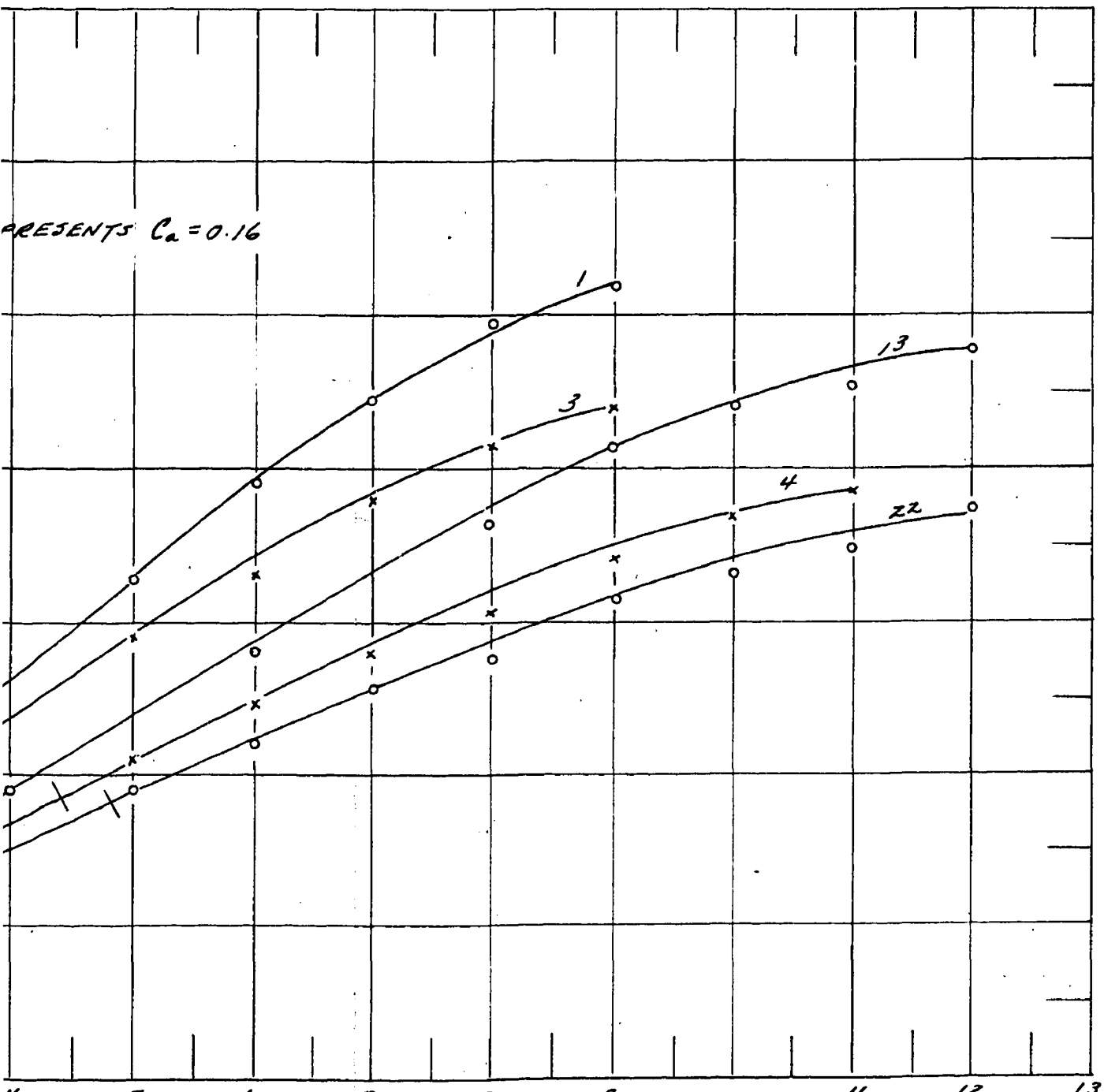


FIGURE 21 VARIATION OF $\pi^2 Dt/R^2$ WITH TIME - VARIABLE DEN



OF $\pi^2 Dt/\ell^2$ WITH TIME - VARIABLE DEW POINT SERIES - (SOYBEANS)

measured with a micrometer. The mean radius was 0.319 cm. The values of D are given in Table 2 in the Appendix. The value of D calculated for each run in the $C_a = 0.35$ to 0.16 period was then plotted against the dimensionless group $(\frac{P_{sm}-P_w}{P})$ included as Figure 22. Examination of this figure reveals that D bears the following relation to the $(\frac{P_{sm}-P_w}{P})$ group:

$$D = \frac{P_{sm}-P_w+(0.01)P}{(69)(P)} \tag{37}$$

For the second falling rate period, the value of D was calculated for each hour of each run. The diffusivity was then plotted against the log of the dimensionless $(\frac{C_a}{C_o})$ group for each run. These curves are presented in Figure 23. It may be noted that with the exception of run 13, all of the curves have approximately the same slope. This indicates that the P_1 terms considered should combine as a product which, in fact, was done. Thus, the diffusivity of all of the runs may be expressed as:

$$D = \frac{\log \frac{C_a}{bC_o}}{770} \tag{38}$$

where b is a different constant for each run. Then, the value of b was calculated for each of the curves. Figure 24 represents a plot of log b against log $(\frac{P_{sm}-P_w}{P})$. Accordingly, b may be expressed in terms of the $(\frac{P_{sm}-P_w}{P})$ group as:

$$b = \left[\frac{0.0088P}{P_{sm}-P_w}\right]^{1.63} \tag{39}$$

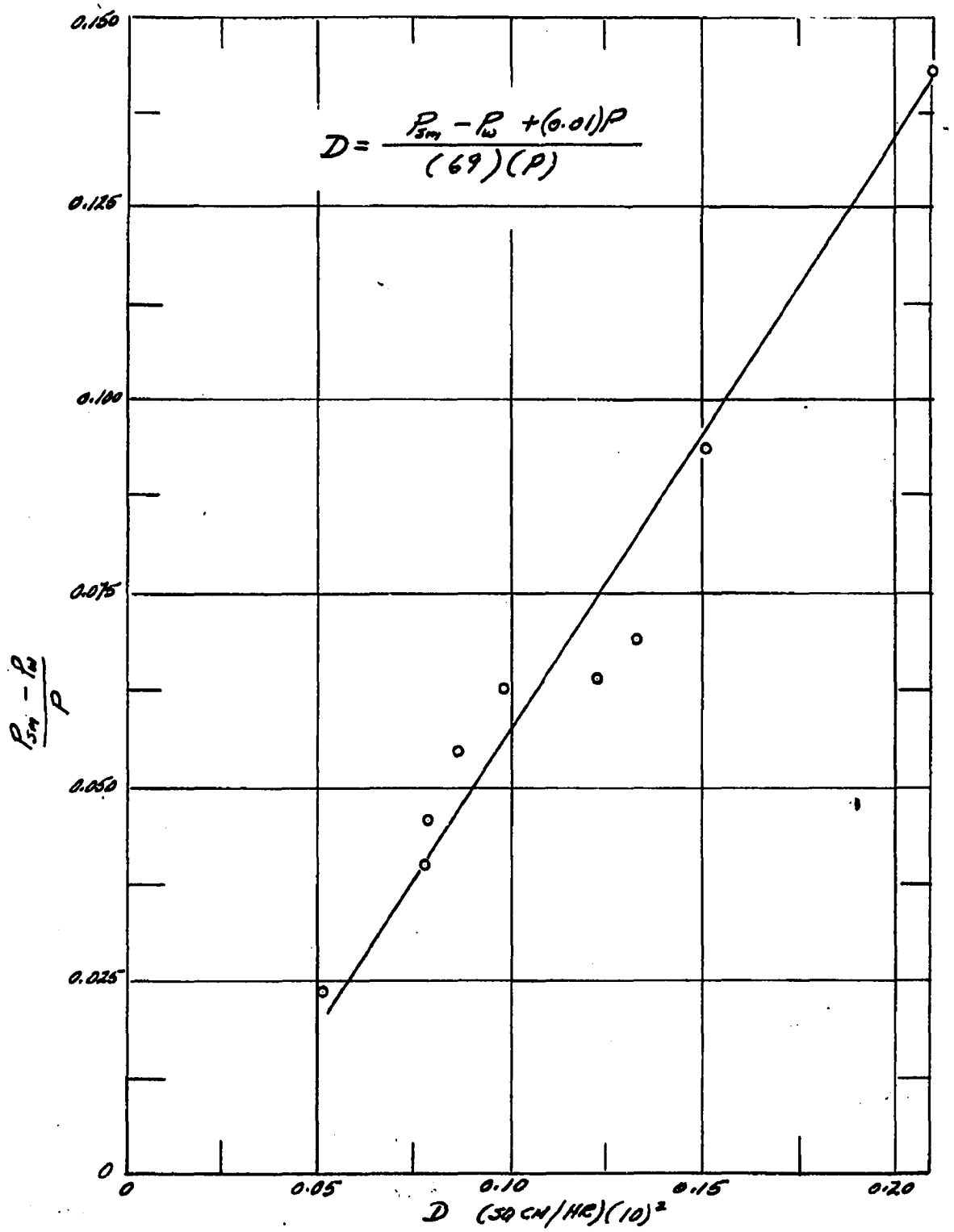


FIGURE 22
VARIATION OF DIFFUSIVITY WITH $\frac{P_{sm} - P_w}{P}$ FOR VALUES OF C_w GREATER THAN 0.16
(SOYBEANS)

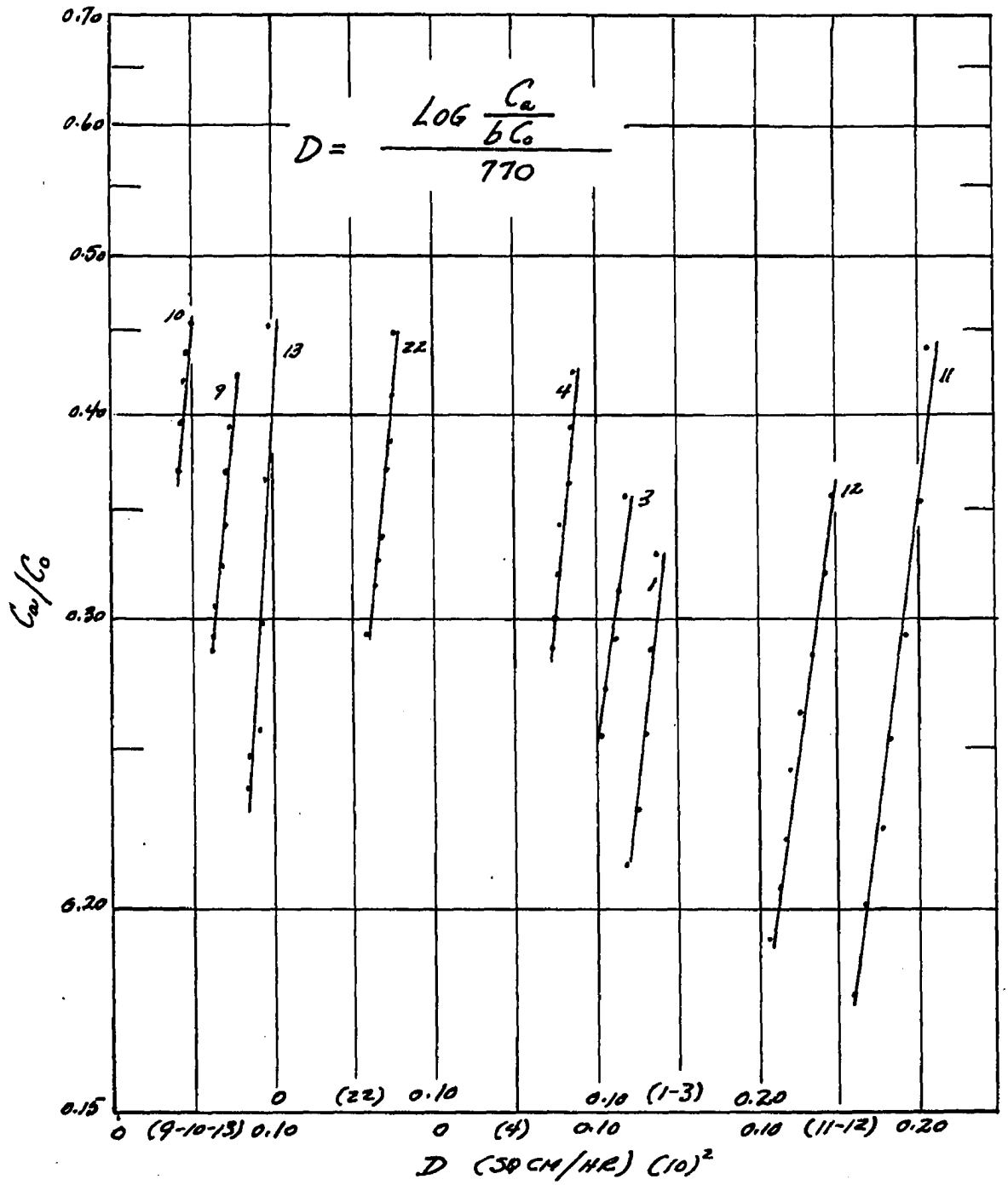


FIGURE 23
VARIATION OF DIFFUSIVITY WITH Ca/Co FOR VALUES OF D BELOW Ca = 0.16 (SOYBEANS)

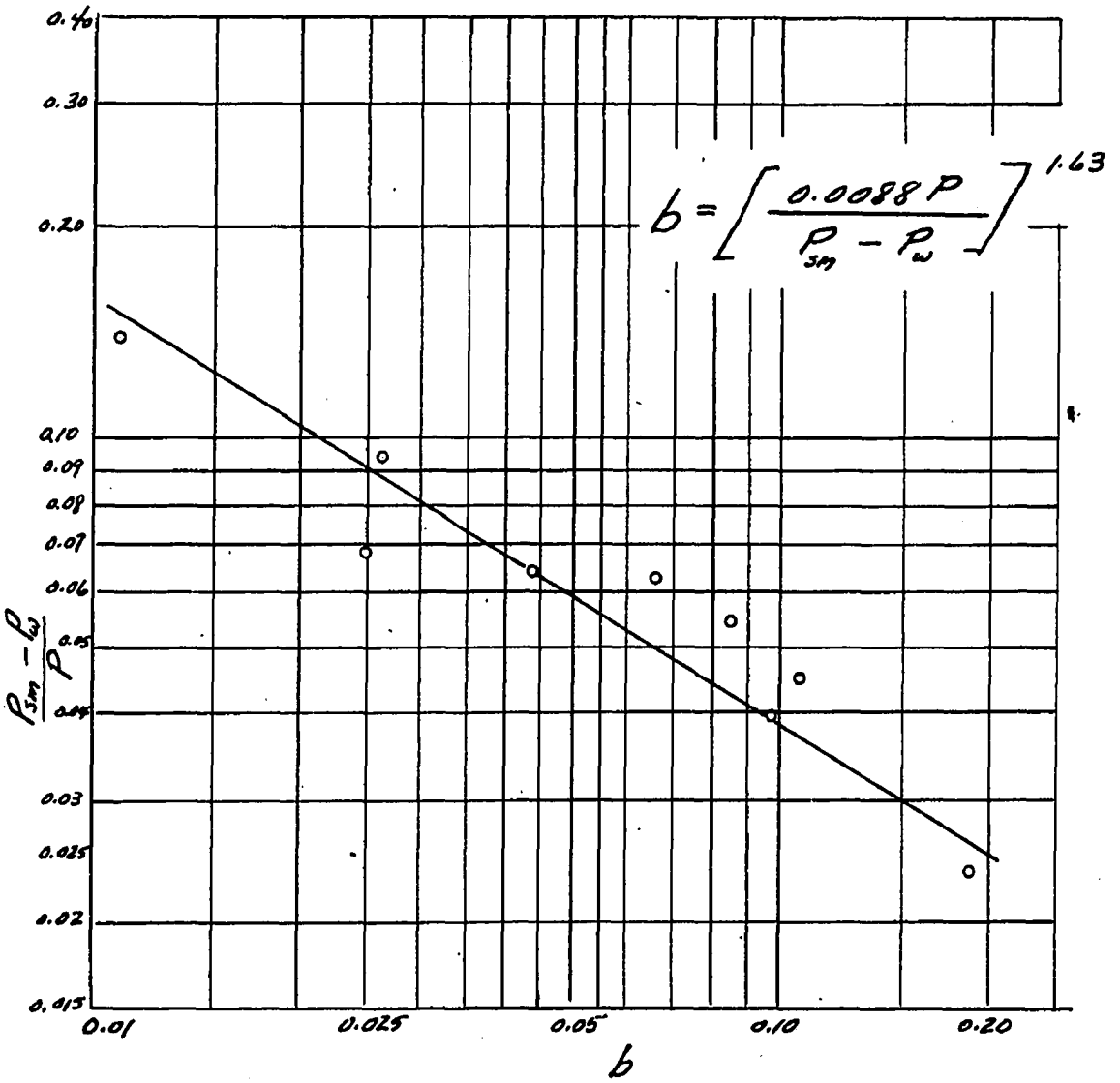


FIGURE 24
VARIATION OF CONSTANT b WITH $\frac{P_{sm} - P_w}{P}$
(SOYBEANS)

By combining equations (38) and (39) the following expression is obtained for the diffusivity in the second (below C_a=0.16) falling rate period:

$$D = \frac{\log\left[\dfrac{C_a}{C_o\left(\dfrac{0.0088P}{P_{sm}-P_w}\right)^{1.63}}\right]}{770} \qquad (40)$$

Thus, the diffusivity in the diffusion equation is a property depending upon both the material and the drying environment.

Illustrative Problem

An illustrative problem is included to indicate how a drying problem may be solved with the use of the method developed.

To calculate the time required to dry a tray of soybeans initially with an average moisture concentration of 0.35 to an average moisture concentration of 0.10, air is to be supplied at 150°F with a 46.5°F dew point, at a velocity of 38 fpm. The following additional data are given:

Barometer = 28.86 in. Hg

Radius of bean = 0.319 cm

These are the same test conditions used in run 11, with the C-time curve given in Figure 14. For the first falling rate period:

$$\frac{C_a}{C_o} = \frac{0.16}{0.35} = 0.457$$

with the use of equation (31)

$$\frac{C_a}{C_o} = 0.534 = \frac{6}{n^2\pi^2} \sum_{1}^{\infty} (\exp) - \frac{n^2\pi^2 Dt}{R^2}$$

$$\frac{\pi^2 Dt}{R^2} = 0.37 \qquad \text{(see Table 2)}$$

$P = 28.86$ in. Hg

$P_w = 0.318$ in. Hg

$P_s = 7.572$ in. Hg (at dry bulb temperature, 150°F)

$P_s = 1.032$ in. Hg (at wet bulb temperature, 80°F)

$$P_{sm} = \frac{7.572 + 1.032}{2} = 4.302 \text{ in. Hg}$$

$$P_{sm} - P_w = \frac{4.302 - 0.318}{28.86} = 0.138$$

According to equation (37):

$$D = \frac{(4.302 - 0.318) + (0.01)(28.86)}{(69)(28.86)} = 0.00214 \text{ sq cm/hr}$$

$$\frac{\pi^2 Dt}{R^2} = 0.37$$

$$t = \frac{(0.37)(0.319)^2}{(3.1416)^2\ (0.00214)} = 1.79 \text{ hr}$$

In referring to Figure 14 it may be observed that the time re-

quired (run 11) to dry to C = 0.16 is 1.81 hours. The time required to dry from C = 0.16 to C = 0.10 may be calculated by calculating the time required to dry the soybeans to C = 0.10 from C = 0.35 and subtracting the time calculated for drying to C = 0.16 from C = 0.35. A mean value of D at C = 0.13 will be used. For greater precision, successive increments may be taken between C = 0.16 and C = 0.10 with a value of D calculated for each increment.

According to equation (40):

$$D = \frac{\log\left[\frac{C_a}{C_o\left(\frac{0.0088P}{P_{sm}-P_w}\right)^{1.63}}\right]}{770}$$

for $C_a = 0.13$:

$$D = \frac{\log\left[\frac{13}{35\left(\frac{0.0088}{0.138}\right)^{1.63}}\right]}{770}$$

$$D = \frac{\log(32.3)}{770} = \frac{1.5092}{770} = 0.00196 \text{ sq cm/hr}$$

$$\frac{\pi^2 Dt}{R^2} = 0.78 \qquad (C_a/C_o = 10/35)$$

$$t = \frac{(0.78)(0.319)^2}{(3.1416)^2\ (0.00196)} = 4.09 \text{ hr} \quad (C = 0.35 \text{ to } C = 0.16)$$

$$\frac{\pi^2 Dt}{R^2} = 0.37 \qquad (C_a/C_o = 16/35)$$

$$t = \frac{(0.37)(0.319)^2}{(3.1416)^2\ (0.00196)} = 1.94 \text{ hr} \quad (C = 0.35 \text{ to } C = 0.16)$$

Thus, the time required to dry the soybeans from C = 0.16 to C = 0.10 is 2.15 hours. By comparison, the time required for this drying in run 11 taken from Figure 14 is 2.2 hours. The total time required to dry from C = 0.35 to C = 0.10 is equal to 1.79 + 2.15 = 3.94 hours, compared to the experimental value of 4.03 hours.

Treatment of Corn Data

Examination of the corn drying curves, in comparison to the soybean curves for the same drying conditions, show that initially the corn drys faster than soybeans, and after several hours drys at a slower rate than the soybeans.

The soybean curves were interpreted again, and the moisture concentration for each hour determined for zero time at C = 0.30. This initial moisture concentration corresponds to the starting point in all of the corn tests. Then, using $C_o = 0.30$, values for $(\frac{\pi^2 Dt}{R^2})$ were calculated with equation (31). These data are included in the Appendix as Table 3. Then, the values of $(\frac{\pi^2 Dt}{R_e^2})$ were calculated in a similar manner for the corn, and given in Table 4. The F factor for the corn defined as:

$$F = \frac{(\frac{\pi^2 Dt}{R_e^2})\text{corn}}{(\frac{\pi^2 Dt}{R^2})\text{soybeans}} \qquad (41)$$

was then calculated, where the $(\frac{\pi^2 Dt}{R^2})$ groups of each set of data were compared at the same time and for identical values of $(\frac{P_{sm}-P_w}{P})$. A graphical representation of $(\frac{\pi^2 Dt}{R_e^2})$ corn versus $(\frac{\pi^2 Dt}{R^2})$ soybeans is presented in Figure 25.

An F factor of F = 1.1 was obtained for corn moisture concentrations above 0.16. In the range of C_a below 0.16 the factor is expressed as:

$$F = \frac{0.12}{(\frac{\pi^2 Dt}{R^2})\ soybeans} + 0.67 \qquad (42)$$

The drying characteristics of corn kernels may be predicted from corresponding soybean data with the use of the F factors given.

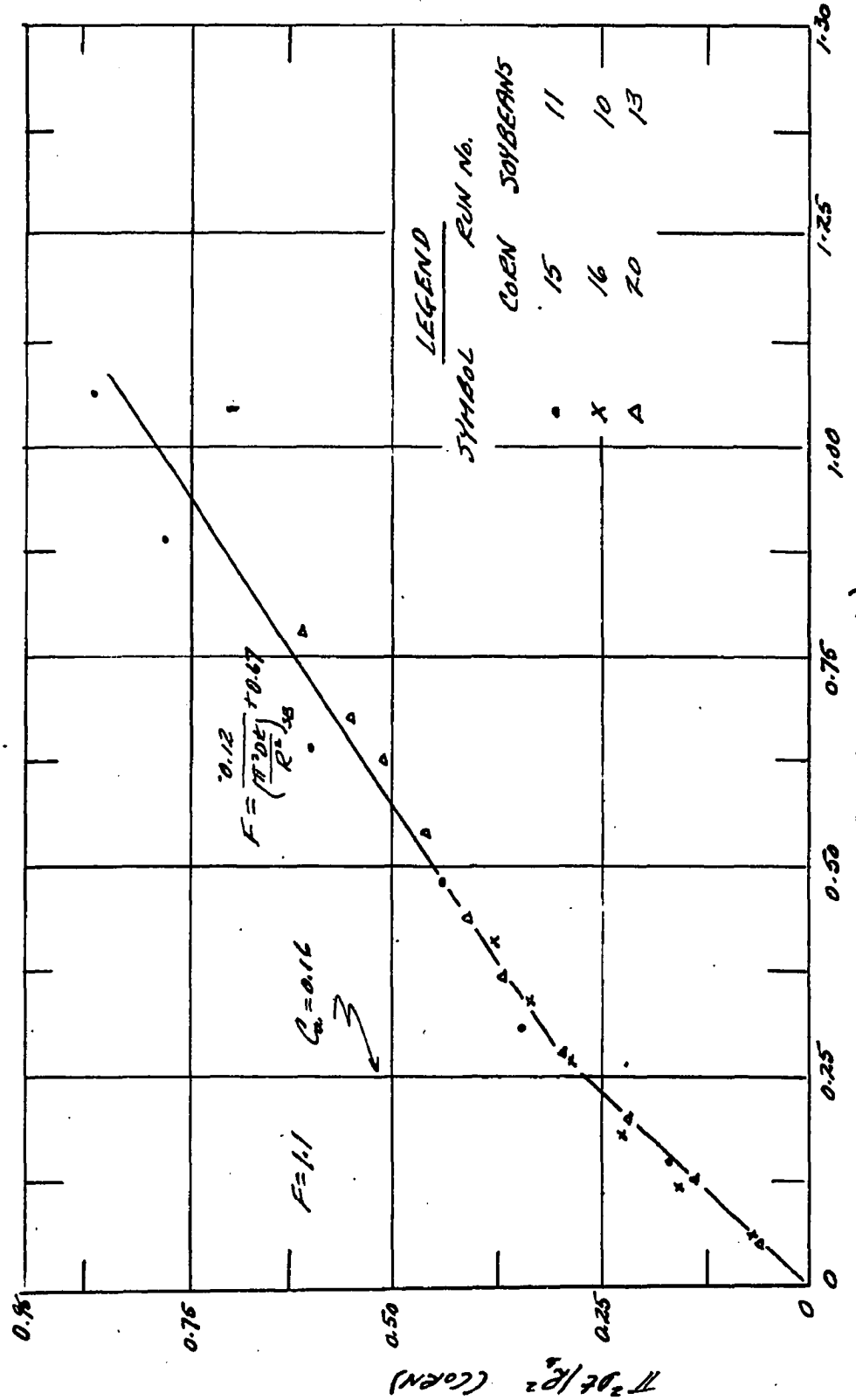


FIGURE 25
VARIATION OF $\pi^2 Dt/R^2$ GROUP OF CORN WITH SOYBEANS FOR SAME DRYING CONDITIONS

CONCLUSIONS

The following conclusions are derived from the theoretical and experimental investigations presented herein, and are considered applicable in the range of drying conditions studied:

1. The basic mechanism of resembling diffusion may be assumed for the moisture movement in the drying of soybeans.

2. Drying of soybeans is accomplished in two falling rate periods. The first falling rate period terminates at an average moisture concentration of approximately 0.16.

3. During the first falling rate period the diffusivity of soybeans remains constant, while during the second period the diffusivity decreases with decreasing moisture concentrations.

4. Diffusivity is a property dependent upon both the material and the drying environment.

5. The drying characteristics of corn may be predicted from soybean drying data with the use of an F factor presented.

REFERENCES

1. Sherwood, T. K. and Comings, E. W. The mechanism of the drying of clays. Trans. American Inst. Chem. Engr. 28:118. 1932.

2. Sherwood, T. K. Air drying of solids. Chem. Engr. Congress World Power Conference 2:346. 1936.

3. Marshall, W. R. Through circulation drying. Unpublished Ph.D. Thesis. Madison, Wisconsin, University of Wisconsin Library. 1941. p. 104.

4. Newman, A. B. The drying of porous solids: Diffusion and surface emission equations. Trans. American Inst. Chem. Engr. 27:203. 1931.

5. Sherwood, T. K. Application of theoretical diffusion equations to the drying of solids. Trans. American Inst. Chem. Engr. 27:190. 1931.

6. Newman, A. B. The drying of porous solids: Diffusion calculations. Trans. American Inst. Chem. Engr. 27:310. 1931.

7. Hougen, O. A. and McCauley, H. J. Limitations of diffusion equations in drying. Trans. American Inst. Chem. Engr. 36:183. 1941.

8. Smith, D. E. Effect of drying conditions upon the biochemical properties of corn. Unpublished Ph.D. Thesis. Minneapolis, Minnesota, University of Minnesota Library. 1948. p. 64.

9. Goff, J. A. Thermodynamic properties of moist air. In Heating Ventilating and Air Conditioning Guide. Published by ASHVE. 29 ed. 1951. p. 32-40.

ACKNOWLEDGMENT

The writer wishes to acknowledge his indebtedness to Dr. Glenn Murphy, Professor of Theoretical and Applied Mechanics, for invaluable advice and encouragement during the course of the investigation. Thanks are due as well to Professor H. M. Black, Head of the Department of Mechanical Engineering, for suggesting this study of drying agricultural products, and for his intellectual stimulation and continued interest in the project.

Grateful acknowledgment is also made to Professor R. W. Breckenridge for an excellent job of sheet metal fabrication in the building of the drier.

APPENDIX

Table 1

Values of Correction Factor Z for Wet Bulb Temperatures[a]

Ts °F	Z Max	Z Min	Z Ave
32	0.00343	0.00347	0.0035
50	0.00765	0.00756	0.0076
60	0.0105	0.0101	0.0103
70	0.0157	0.0154	0.0155
80	0.0229	0.0221	0.0225
90	0.0310	0.0303	0.0307
100	0.0433	0.0427	0.0430
110	0.0591	0.0582	0.0587
120	0.0808	0.0792	0.0800
130	0.1108	0.1099	0.1104
140	0.1529	0.1513	0.1521
150	0.2110	0.2110	0.2110

[a]Dry bulb temperature range 32°F to 150°F.

Table 2

Calculated Data For Drying Curves (Soybeans)

Run	Time hr	C_a/C_o	$\pi^2 Dt/R^2$	$D(10)^2$ sq cm/hr	$\frac{P_{sm}-P_w}{P}$	b
10	0	1.0	0.0		0.024	0.1880
	2	0.678	0.11	0.051		
	4	0.585	0.19	0.051		
	6	0.516	0.28	0.051		
	8	0.456	0.37	0.051		
	9	0.438	0.41	0.047		
	10	0.420	0.44	0.045		
	11	0.402	0.46	0.043		
	12	0.396	0.49	0.0424		
	13	0.368	0.53	0.0424		
9	0	1.0	0.0		0.040	0.0974
	2	0.616	0.16	0.078		
	4	0.500	0.30	0.078		
	6	0.422	0.43	0.078		
	7	0.394	0.49	0.072		
	8	0.366	0.56	0.072		
	9	0.343	0.61	0.071		
	10	0.323	0.67	0.069		
	11	0.306	0.72	0.065		
	12	0.294	0.75	0.064		
	13	0.286	0.78	0.062		
13	0	1.0	0.0		0.063	0.0666
	2	0.586	0.19	0.098		
	4	0.454	0.38	0.098		
	6	0.366	0.56	0.096		
	8	0.300	0.73	0.094		
	9	0.271	0.83	0.095		
	10	0.257	0.88	0.091		
	11	0.249	0.91	0.086		
	12	0.237	0.96	0.083		

Table 2 (Continued)

Run	Time hr	C_a/C_o	π^2Dt/R^2	$D(10)^2$ sq cm/hr	$\frac{P_{sm}-P_w}{P}$	b
12	0	1.0	0.0		0.094	0.0266
	2	0.506	0.29	0.151		
	3	0.421	0.44	0.151		
	4	0.357	0.57	0.147		
	5	0.320	0.68	0.142		
	6	0.285	0.78	0.134		
	7	0.263	0.86	0.127		
	8	0.243	0.93	0.120		
	9	0.220	1.03	0.118		
	10	0.206	1.08	0.111		
	11	0.191	1.14	0.107		
11	0	1.0	0.0		0.138	0.0110
	1	0.571	0.21	0.210		
	2	0.44	0.40	0.206		
	3	0.354	0.59	0.202		
	4	0.294	0.76	0.196		
	5	0.254	0.89	0.183		
	6	0.224	1.04	0.178		
	7	0.200	1.12	0.164		
	8	0.176	1.24	0.159		
1	0	1.0	0.0		0.069	0.0250
	1	0.657	0.13	0.134		
	3	0.448	0.38	0.134		
	5	0.328	0.66	0.136		
	6	0.286	0.78	0.134		
	7	0.255	0.89	0.131		
	8	0.229	0.99	0.128		
	9	0.212	1.04	0.119		

Table 2 (Continued)

Run	Time hr	C_a/C_o	$\pi^2 Dt/R^2$	$D(10)^2$ sq cm/hr	$\frac{P_{sm}-P_w}{P}$	b
3	0	1.0	0.0		0.064	0.0436
	1	0.670	0.11	0.123		
	3	0.457	0.37	0.123		
	5	0.358	0.58	0.119		
	6	0.323	0.66	0.113		
	7	0.291	0.76	0.112		
	8	0.271	0.83	0.107		
	9	0.255	0.88	0.101		
4	0	1.0	0.0		0.055	0.0851
	1	0.725	0.08	0.086		
	3	0.534	0.25	0.086		
	5	0.429	0.42	0.086		
	6	0.394	0.49	0.084		
	7	0.363	0.56	0.082		
	8	0.343	0.61	0.079		
	9	0.320	0.68	0.078		
	10	0.300	0.74	0.076		
	11	0.289	0.77	0.074		
22	0	1.0	0.0		0.046	0.1054
	1	0.729	0.08	0.079		
	3	0.557	0.23	0.079		
	5	0.450	0.38	0.078		
	6	0.411	0.44	0.076		
	7	0.386	0.51	0.075		
	8	0.371	0.55	0.071		
	9	0.337	0.63	0.070		
	10	0.326	0.66	0.068		
	11	0.315	0.69	0.065		
	13	0.295	0.75	0.060		

Table 3

Calculated Data for Drying Curves (Soybeans)[a]

Run	Time hr	C_a/C_o	$\pi^2 Dt/R^2$	$\frac{P_{sm}-P_w}{P}$
11	0	1.000	0.00	0.138
	1	0.634	0.15	
	2	0.490	0.31	
	3	0.400	0.48	
	4	0.333	0.64	
	6	0.253	0.89	
	8	0.200	1.12	
10	0	1.000	0.00	0.024
	2	0.760	0.06	
	4	0.660	0.12	
	6	0.596	0.18	
	8	0.523	0.27	
	10	0.473	0.34	
	12	0.437	0.41	
13	0	1.000	0.00	0.063
	1	0.760	0.05	
	2	0.656	0.13	
	3	0.577	0.20	
	4	0.513	0.28	
	5	0.460	0.37	
	6	0.416	0.44	
	7	0.377	0.54	
	8	0.337	0.63	
	9	0.316	0.68	
	10	0.300	0.72	
	11	0.283	0.78	

[a]Recalculated for $C_o = 0.30$.

Table 4

Calculated Data for Drying Curves (Corn)

Run	Time hr	C_a/C_o	$\pi^2 Dt/R_e^2$	$\frac{P_{sm}-P_w}{P}$
15	0	1.000	0.00	0.135
	1	0.600	0.17	
	2	0.466	0.35	
	3	0.402	0.44	
	4	0.347	0.60	
	6	0.283	0.78	
	8	0.263	0.86	
	10	0.233	0.97	
	11	0.220	1.01	
16	0	1.000	0.00	0.025
	2	0.732	0.07	
	4	0.620	0.16	
	6	0.554	0.23	
	8	0.506	0.29	
	10	0.470	0.34	
	12	0.452	0.38	
	14	0.440	0.40	
20	0	1.000	0.00	0.063
	1	0.757	0.06	
	2	0.642	0.14	
	3	0.562	0.22	
	4	0.504	0.30	
	5	0.460	0.37	
	6	0.436	0.41	
	7	0.410	0.46	
	8	0.387	0.51	
	9	0.370	0.55	
	11	0.346	0.61	

Drying Rate Experimental Data

Barometer: 29.06 in. Hg Date: Feb. 6, 1951
Sample: Soybeans Run No.: 1
Average air inlet temperature: 120 °F
Average exit air velocity: 1590 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 69 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	948.4	935.3	950.3	949.8
½	906.1	890.4	911.0	908.3
1	892.1	876.0	895.7	893.3
1½	881.8	864.4	885.6	883.8
2	875.8	858.0	878.4	877.5
3	866.2	847.3	869.3	868.4
4	859.7	839.5	862.0	860.8
5	854.7	834.3	857.0	854.9
7	846.0	825.8	848.3	847.4
9	838.0	818.8	847.4	846.9
Tare tray	525.0	54.8	525.4	525.1

Final Moisture Determination

Treatment: 16 hr - 90°C, 30 in. Hg vacuum (gage)

	Box number			
	1	2	3	4
Gross weight (grams)	52.7721	48.9153	52.3589	62.1970
Final weight (grams)	51.4870	46.7950	49.6820	59.8970
Tare box (grams)	29.3975	21.8860	20.2954	36.6860
Dry solid (grams)	22.09	24.91	29.39	23.21
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0585	0.0853	0.0914	0.0990

Drying Rate Experimental Data

Barometer: 29.07 in. Hg Date: Feb. 10, 1951
Sample: Soybeans Run No: 2
Average air inlet temperature: 120 °F
Average exit air velocity: 1595 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 73 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	934.0	913.3	928.3	928.5
½	903.0	887.5	903.0	893.0
1	888.7	878.5	893.1	880.5
1½	882.4	871.6	887.0	872.0
2	876.3	866.3	880.8	865.8
3	867.1	857.8	872.7	856.4
4	862.0	854.3	868.8	850.9
5	856.4	849.2	863.5	845.0
6	852.7	845.3	860.2	841.3
7	851.0	842.0	858.5	838.3
10	850.7	841.8	855.4	838.0

Final Moisture Determination

Treatment: 16 hr - 90°C, 30 in Hg vacuum (gage)

	Box number			
	1	2	3	4
Gross weight (grams)	54.7200	60.1820	57.1620	52.6140
Final weight (grams	52.4910	57.6019	54.8471	50.6019
Tare box (grams)	24.4300	24.5155	24.1400	24.5920
Dry solid (grams)	28.06	33.08	30.71	26.01
Water removed (grams)	2.23	2.58	2.31	2.01
$C \frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0795	0.0790	0.0752	0.0780

Drying Rate Experimental Data

Barometer: 29.39 in. Hg
Date: Feb. 15, 1951
Sample: Soybeans
Run No: 3
Average air inlet temperature: 120 °F
Average exit air velocity: 1590 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 132 °F (Dry bulb)
Average air supply temperature: 73 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	971.2	953.1	971.3	964.5
½	925.5	909.2	925.0	916.8
1	913.2	896.7	912.0	904.4
1½	905.1	889.4	906.8	897.5
2	900.0	882.9	898.5	890.7
3	891.0	873.6	890.0	881.8
4	885.1	868.8	883.7	876.3
5	879.8	863.9	879.8	870.7
7	872.4	855.9	871.4	863.8
9	867.1	851.6	866.8	859.3

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number			
	5	6	7	8
Gross weight (grams)	60.124	55.930	57.093	59.463
Final weight (grams)	57.201	53.203	54.381	56.654
Tare box (grams)	24.024	24.511	25.015	24.455
Dry solid (grams)	33.18	28.69	29.36	32.20
Water removed (grams)	2.92	2.73	2.71	2.81
$C \frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0882	0.0950	0.0922	0.0875

Drying Rate Experimental Data

Barometer: 29.06 in. Hg Date: Feb. 17,1951
Sample: Soybeans Run No: 4
Average air inlet temperature: 120 °F
Average exit air velocity: 1590 fpm
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 126 °F (Dry bulb)
Average air supply temperature: 82 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	950.0	938.7	952.5	952.7
½	920.4	905.5	918.9	917.1
1	908.8	891.4	905.2	902.3
1½	900.6	882.8	896.9	894.8
2	894.2	877.0	889.4	889.0
3	886.2	866.6	880.4	879.8
4	880.7	859.4	873.3	872.1
5	876.7	855.3	868.2	868.5
7	869.5	849.2	861.4	862.0
8	866.3	845.4	858.6	858.6
11	859.7	838.8	852.2	852.3

Final Moisture Determination

Treatment: 18 hr - 100°C, 30 in. Hg vacuum (gage)

	Box number			
Gross weight (grams)	61.186	61.270	55.490	58.378
Final weight (grams)	57.796	57.880	52.258	55.196
Tare box (grams)	24.024	24.511	25.015	24.455
Dry solid (grams)	33.77	33.369	27.24	30.74
Water removed (grams)	3.39	3.39	3.23	3.18
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.100	0.101	0.117	0.103

Drying Rate Experimental Data

Barometer: 29.15 in. Hg Date: Feb. 20, 1951
Sample: Soybeans Run No: 5
Average air inlet temperature: 120 °F
Average exit air velocity: 1225 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	954.2	942.3	953.8	957.9
½	914.4	904.0	915.1	916.8
1	903.1	891.8	901.3	903.9
1½	892.9	883.3	893.8	895.2
2	817.0	875.3	886.4	888.2
3	877.1	865.9	875.9	876.5
4	870.0	860.2	870.0	870.7
5	863.6	854.4	863.5	865.3
7	856.8	846.3	855.8	856.7
9	850.9	941.2	850.0	852.1
11	845.9	836.7	846.1	847.3

Final Moisture Determination

Treatment: 18 hr - 100°C, 30 in. Hg vacuum (gage)

	Box number			
	1	2	3	4
Gross weight (grams)	57.272	61.276	56.939	59.571
Final weight (grams)	54.787	58.451	54.438	56.988
Tare box (grams)	24.430	24.516	24.140	24.592
Dry solid (grams)	30.357	33.935	30.298	32.396
Water removed (grams)	2.485	2.825	2.501	2.583
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.082	0.083	0.083	0.082

Drying Rate Experimental Data

Barometer: 28.66 in. Hg Date: Feb. 25, 1951
Sample: Soybeans Run No: 6
Average air inlet temperature: 120 °F
Average exit air velocity: 1595 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 79 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	956.1	940.5	950.3	951.1
½	919.8	905.0	916.8	914.9
1	909.8	894.5	904.3	903.5
1½	901.4	892.4	897.8	899.5
2½	897.1	884.4	893.8	894.0
3½	892.3	880.2	886.2	888.6
4½	887.9	876.1	883.8	882.0
6½	882.0	869.3	879.0	879.0
9½	875.0	861.5	872.0	870.6

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number			
	A	B	C	D
Gross weight (grams)	54.666	54.868	55.938	54.517
Final weight (grams)	52.119	52.255	53.308	51.963
Tare box (grams)	24.048	24.514	24.261	24.305
Dry solid (grams)	28.071	27.741	29.047	27.658
Water removed (grams)	2.547	2.613	2.630	2.554
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0908	0.0940	0.0905	0.0923

Drying Rate Experimental Data

Barometer: 29.23 in. Hg Date: Feb. 28, 1951
Sample: Soybeans Run No: 7
Average air inlet temperature: 120 °F
Average exit air velocity: 2120 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	953.9		953.0	948.5
½	913.5		916.2	914.8
1	903.9		907.2	904.8
2	891.9		894.8	891.9
3	882.7		885.2	882.7
4	875.6		879.6	877.0
6	869.0		870.2	870.5
8	863.3		865.3	862.6
10	859.4		860.8	858.6
Air dried	850.0		851.7	849.0

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	4	1
Gross weight (grams)	52.0399	48.3043
Final weight (grams)	50.471	46.935
Tare box (grams)	24.592	24.430
Dry solid (grams)	25.879	22.505
Water removed (grams)	1.569	1.369
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0606	0.0608

Drying Rate Experimental Data

Barometer: 29.06 in. Hg Date: March 3, 1951
Sample: Soybeans Test No: 8
Average air inlet temperature: 120 °F
Average exit air velocity: 1000 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	963.2	955.0	966.0	965.4
½	927.6	920.0	931.4	930.5
1	914.3	906.3	918.6	918.1
1½	904.5	897.1	908.2	909.0
2½	893.0	885.0	896.0	897.1
3½	883.9	877.2	889.3	889.8
4½	879.2	871.6	883.0	884.2
7	868.8	862.2	873.1	875.4
10	861.6	855.5	866.5	868.3
Air dried	848.6	840.4	851.1	853.5

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	1	4
Gross weight (grams)	45.164	40.511
Final weight (grams)	44.256	39.809
Tare box (grams)		
Dry solid (grams)	19.826	15.217
Water removed (grams)	0.908	0.702
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0458	0.0462

Drying Rate Experimental Data

Barometer: 28.76 in. Hg
Date: March 22, 1951
Sample: Soybeans
Run No: 9
Average air inlet temperature: 105 °F
Average exit air velocity: 1600 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 104 °F
Average air supply temperature: 110 °F (Dry bulb)
Average air supply temperature: 70 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	955.9	950.1	958.6	956.2
½	927.4	923.3	930.0	930.2
1	918.0	913.5	920.0	920.4
1½	910.3	906.7	912.5	912.8
2½	902.0	898.7	904.1	903.4
4½	890.0	886.7	893.2	891.5
6½	882.1	879.9	885.1	884.2
8½	876.1	874.5	879.8	878.3
11	871.5	869.1	875.2	873.6
13	868.4	866.1	872.2	870.5
Air dried	865.0	861.2	868.3	867.5

Final Moisture Determination

Treatment: 16 hr, 95°C, 30 in. Hg vacuum (gage)

	Box number	
	B	3
Gross weight (grams)	45.851	45.577
Final weight (grams)	44.109	43.825
Tare box (grams)	24.514	24.140
Dry solid (grams)	19.595	19.685
Water removed (grams)	1.742	1.752
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0888	0.0892

Drying Rate Experimental Data

Barometer: 29.20 in. Hg Date: March 23, 1951
Sample: Soybeans Run No: 10
Average air inlet temperature: 90 °F
Average exit air velocity: 1620 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 89 °F
Average air supply temperature: 92 °F (Dry bulb)
Average air supply temperature: 64 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	956.2	946.4	952.6	951.1
½	931.6	921.5	929.5	925.3
1	918.3	909.0	915.8	911.8
2	910.8	900.3	908.2	905.0
4	900.7	890.0	898.1	894.7
7	891.0	880.0	887.9	884.2
10	884.0	872.8	881.3	878.6
13	878.0	867.5	875.8	872.9
Air dried	855.0	843.6	851.6	850.0

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	C	D
Gross weight (grams)	44.498	46.299
Final weight (grams)	43.515	45.223
Tare box (grams)	24.261	24.305
Dry solid (grams)	19.254	20.918
Water removed (grams)	0.983	1.076
$C \frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0510	0.0513

Drying Rate Experimental Data

Barometer: 28.86 in. Hg Date: March 26, 1951
Sample: Soybeans Run No: 11
Average air inlet temperature: 150 °F
Average exit air velocity: 1595 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 146 °F
Average air supply temperature: 150 °F (Dry bulb)
Average air supply temperature: 80 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	955.6	940.6	957.8	956.7
½	914.3	901.4	918.0	916.9
1	902.0	888.8	904.5	904.0
1½	893.7	880.8	895.8	895.0
2	886.7	874.6	889.7	888.4
3	877.3	865.5	880.5	879.7
4	871.2	860.0	874.5	873.2
6	862.5	850.5	865.6	864.1
8	857.1	846.1	859.8	859.1
Air dried	856.5	844.2	858.8	858.7

Final Moisture Determination

Treatment: 16 hr. - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	2	A
Gross weight (grams)	48.583	43.303
Final weight (grams)	47.270	42.232
Tare box (grams	24.516	24.048
Dry solid (grams)	22.754	18.184
Water removed (grams)	1.313	1.071
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0578	0.0588

Drying Rate Experimental Data

Barometer: 28.92 in. Hg Date: March 21, 1951
Sample: Soybeans Run No: 12
Average air inlet temperature: 135 °F
Average exit air velocity: 1610 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 132 °F
Average air supply temperature: 140 °F (Dry bulb)
Average air supply temperature: 78 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	955.9	945.4	956.6	955.3
½	917.7	907.5	921.0	919.0
1	906.8	896.7	909.7	908.0
1½	899.3	887.2	901.8	900.0
2	893.4	881.7	896.1	894.3
3	884.3	873.3	886.9	885.5
5	873.2	861.0	876.0	874.7
8	863.7	850.7	865.3	864.7
11	859.0	846.5	860.4	859.4
Air dried	856.6	843.6	858.3	858.2

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	3	B
Gross weight (grams)	48.782	48.342
Final weight (grams)	47.399	47.017
Tare box (grams)	24.140	24.514
Dry solid (grams)	23.259	22.503
Water removed (grams)	1.383	1.325
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0593	0.0588

Drying Rate Experimental Data

Barometer: 29.02 in. Hg Date: April 1, 1951
Sample: Soybeans Run No: 13
Average air inlet temperature: 120 °F
Average exit air velocity: 1600 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	959.3	946.2	953.0	965.3
½	930.0	916.1	924.6	933.6
1	919.8	906.4	914.5	922.9
2	908.5	894.2	901.6	910.8
3	900.0	886.9	894.4	902.5
4	893.7	880.1	887.8	895.1
5	888.3	875.1	882.4	890.0
7	880.4	868.2	876.0	883.6
9	873.2	860.0	868.7	876.2
12	870.6	857.3	866.1	873.5
Air dried	861.2	846.1	855.9	863.6

Final Moisture Determination

Treatment: 16 hr, 95°C, 30 in. Hg vacuum (gage)

	Box number	
	4	A
Gross weight (grams)	54.091	47.114
Final weight (grams)	52.509	45.870
Tare box (grams)	24.592	24.048
Dry solid (grams)	27.917	21.822
Water removed (grams)	1.582	1.244
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0568	0.0568

Drying Rate Experimental Data

Barometer: 29.08 in. Hg Date: April 17, 1951
Sample: Corn Run No: 14
Average air inlet temperature: 120 °F
Average exit air velocity: 1600 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1020.5	1011.5	1025.6	1030.0
½	996.8	990.5	1004.2	1010.0
1	986.0	982.1	994.1	1002.1
2	972.8	972.1	980.9	992.1
3	964.3	963.5	974.0	984.5
5	954.7	955.4	962.3	976.3
8	946.9	947.8	955.9	968.5
11	942.1	943.3	952.5	965.0
Air dried	938.7	939.5	947.3	961.0

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	6	7
Gross weight (grams)	51.670	53.652
Final weight (grams)	49.394	51.311
Tare box (grams)	24.511	25.015
Dry solid (grams)	24.883	28.637
Water removed (grams)	2.276	2.341
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0915	0.0818

Drying Rate Experimental Data

Barometer: 29.08 in. Hg
Date: April 23, 1951
Sample: Corn
Run No: 15
Average air inlet temperature: 150 °F
Average exit air velocity: 1590 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 147 °F
Average air supply temperature: 144 °F (Dry bulb)
Average air supply temperature: 79 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1043.5	1029.6	1046.3	1045.5
½	1008.5	993.1	1012.9	1008.7
1	992.1	978.4	997.0	993.6
2	976.9	961.3	980.6	977.8
3	967.5	953.3	973.4	969.1
5	957.4	943.0	963.7	960.3
7	953.3	937.4	959.4	955.2
9	949.8	934.2	955.6	951.7
11	947.5	931.8	953.1	949.2
Air dried	952.1	936.1	957.8	954.6

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	1	2
Gross weight (grams)	47.958	47.690
Final weight (grams)	46.274	45.965
Tare box (grams)	24.430	24.516
Dry solid (grams)	21.844	21.449
Water removed (grams)	1.684	1.725
$C \frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0769	0.0800

Drying Rate Experimental Data

Barometer: 29.24 in. Hg Date: April 26, 1951
Sample: Corn Run No: 16
Average air inlet temperature: 92 °F
Average exit air velocity: 1585 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 91 °F
Average air supply temperature: 94 °F (Dry bulb)
Average air supply temperature: 65 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1014.8	1006.5	1025.1	1014.5
½	996.2	984.8	1005.0	993.2
1	988.8	975.6	996.3	983.1
2	978.8	964.0	985.1	973.3
3	970.8	957.2	976.7	965.1
5	962.0	945.5	965.2	954.1
8	953.5	936.1	957.0	944.6
11	949.3	930.1	951.0	939.6
14	947.1	929.1	949.5	938.1
Air dried	938.2	918.9	940.0	927.8

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	3	4
Gross weight (grams)	52.525	55.446
Final weight (grams)	49.789	52.456
Tare box (grams)	24.140	24.592
Dry solid (grams)	25.649	27.864
Water removed (grams)	2.736	2.990
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.1062	0.1071

Drying Rate Experimental Data

Barometer: 28.92 in. Hg
Date: April 29, 1951
Sample: Corn
Run No: 17
Average air inlet temperature: 120 °F
Average exit air velocity: 1595 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 86 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1017.6	1003.5	1021.2	1014.3
½	983.0	967.3	989.0	981.9
1	970.1	955.4	976.2	970.6
2	953.5	938.0	958.6	953.4
3	943.8	928.9	949.6	943.8
5	932.0	918.7	937.7	932.6
7	925.5	910.1	930.5	926.9
10	921.8	907.5	926.9	922.3
12	920.0	905.5	925.0	920.3
Air dried	915.9	900.1	921.0	916.1

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	C	D
Gross weight (grams)	51.042	50.854
Final weight (grams)	48.543	48.349
Tare tox (grams)	24.261	24.305
Dry solid (grams)	24.180	24.044
Water removed (grams)	2.499	2.505
$\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.1031	0.1039

Drying Rate Experimental Data

Barometer: 29.04 in. Hg Date: May 1, 1951
Sample: Corn Run No: 18
Average air inlet temperature: 120 °F
Average exit air velocity: 1000 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 126 °F (Dry bulb)
Average air supply temperature: 74 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1013.9	1001.5	1012.8	1016.1
½	972.1	960.0	973.5	973.6
1	947.5	934.0	948.3	948.1
2	906.5	894.8	908.6	907.7
3	881.3	870.0	882.9	882.1
4½	852.2	841.9	853.2	854.0
5½	839.8	830.6	840.8	841.4
8½	821.8	811.6	822.4	824.3
11½	813.5	803.8	813.4	816.2
14½	808.6	798.7	808.6	811.3
Air dried	808.7	798.0	807.7	810.7

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	A	B
Gross weight (grams)	49.679	51.528
Final weight (grams)	47.307	49.105
Tare box (grams)	24.048	24.514
Dry solid (grams)	23.259	24.591
Water removed (grams)	2.372	2.423
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.1018	0.0986

Drying Rate Experimental Data

Barometer: 29.14 in. Hg Date: May 3. 1951
Sample: Corn Run No: 19
Average air inlet temperature: 120 °F
Average exit air velocity: 3180 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1025.9	1013.0	1025.8	1027.6
½	978.0	967.7	979.6	980.2
1½	929.5	920.2	929.3	931.1
2½	895.2	888.3	894.6	896.5
4	863.0	856.3	863.3	864.4
5½	844.5	838.7	845.3	845.8
8	829.5	820.0	830.0	830.6
10½	821.3	811.8	823.1	823.1
13½	812.9	803.2	815.0	814.4
Air dried	817.3	806.7	819.3	818.9

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	6	7
Gross weight (grams)	49.505	47.421
Final weight (grams)	46.989	45.190
Tare box (grams)	24.511	25.015
Dry solid (grams)	22.478	20.175
Water removed (grams)	2.516	2.231
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.1114	0.1107

Drying Rate Experimental Data

Barometer: 29.02 in. Hg Date: May 4, 1951
Sample: Corn Run No: 20
Average air inlet temperature: 120 °F
Average exit air velocity: 1600 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 130 °F (Dry bulb)
Average air supply temperature: 75 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1028.0	1028.0	1028.0	1028.0
½	984.3	875.2	984.2	984.8
1	958.4	849.6	956.6	960.2
2	914.2	905.6	912.6	918.4
3	882.8	874.2	881.1	887.7
4	865.4	857.3	864.2	870.4
6	843.1	835.1	843.2	846.4
8	832.4	824.8	831.2	834.2
11	823.4	817.7	823.4	825.9
14	817.6	812.0	817.0	818.9
Air dried	819.2	811.3	818.2	820.0

Final Moisture Determination

Treatment: 16 hr - 90°C, 30 in. Hg vacuum (gage)

	Box number 5	Box number 8
Gross weight (grams)	50.070	53.725
Final weight (grams)	47.639	50.895
Tare box (grams)	24.024	24.445
Dry solid (grams)	23.615	26.440
Water removed (grams)	2.331	2.830
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0987	0.1062

Drying Rate Experimental Data

Barometer: 29.08 in. Hg Date: May 6, 1951
Sample: Corn Run No: 21
Average air inlet temperature: 120 °F
Average exit air velocity: 1590 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature 118 °F
Average air supply temperature: 125 °F (Dry bulb)
Average air supply temperature: 95 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	1016.2	1003.8	1017.2	1018.5
½	987.6	975.3	987.5	988.2
1	975.5	963.2	976.5	976.5
2	959.1	948.7	961.2	960.8
3	950.5	938.4	950.2	952.1
5	939.1	925.2	941.3	940.0
7	932.0	919.9	933.8	933.2
9	928.4	916.3	928.5	929.6
11	925.9	913.1	926.7	926.4
13	923.8	910.6	923.5	924.3
Air dried	903.2	890.7	904.0	904.3

Final Moisture Determination

Treatment: 16 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number C	Box number D
Gross weight (grams)	54.433	55.297
Final weight (grams)	52.641	53.452
Tare box (grams)	24.261	24.305
Dry solid (grams)	28.380	29.147
Water removed (grams)	1.792	1.845
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0631	0.0633

Drying Rate Experimental Data

Barometer: 29.03 in. Hg Date: June 1, 1951
Sample: Soybeans Run No: 22
Average air inlet temperature: 120 °F
Average exit air velocity: 1610 fpm (Traverse)
Outlet area: 0.353 sq ft
Average exit air temperature: 118 °F
Average air supply temperature: 123 °F (Dry bulb)
Average air supply temperature: 90 °F (Wet bulb)

Time hours	Gross sample weight - grams			
	1	2	3	4
0	972.1	955.3	964.9	969.4
½	934.8	920.2	930.0	932.2
1	920.4	906.5	915.7	918.6
2	906.0	892.5	901.2	904.0
3	896.9	884.2	891.4	895.5
4½	889.8	875.2	884.0	886.8
7½	877.4	865.6	875.3	876.6
10	874.9	862.5	871.3	872.5
13	871.8	859.4	867.9	869.4
Air dried	860.9	848.0	856.7	860.0

Final Moisture Determination

Treatment: 17 hr - 95°C, 30 in. Hg vacuum (gage)

	Box number	
	2	4
Gross weight (grams)	51.510	48.910
Final weight (grams)	49.761	47.312
Tare box (grams)	24.516	24.592
Dry solid (grams)	25.245	22.720
Water removed (grams)	1.749	1.598
C $\frac{\text{Grams } H_2O}{\text{Gram DS}}$	0.0693	0.0702